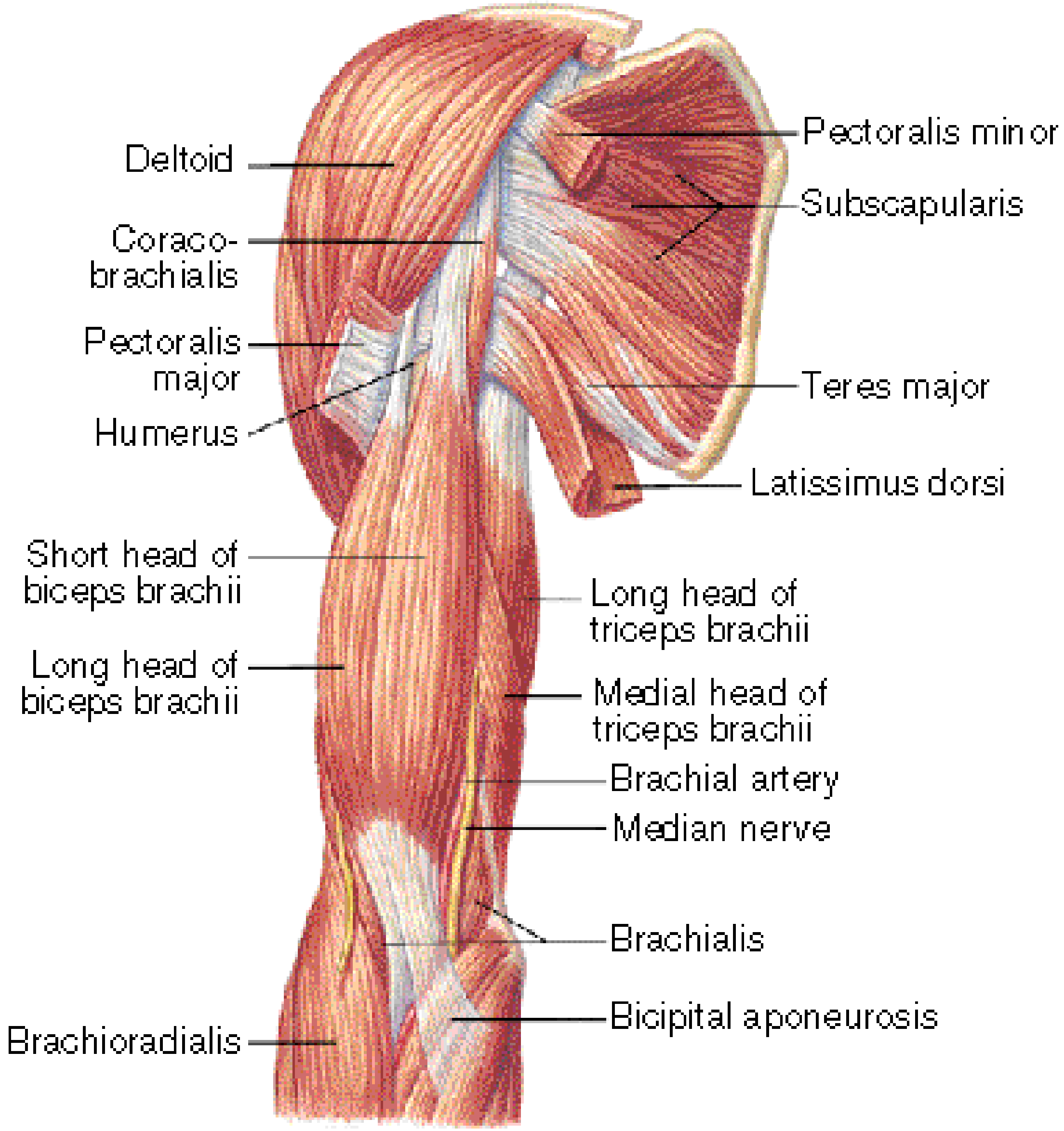
MUSCLE TISSUE



Deltoid
Coraco-
brachialis
Pectoralis
major
Humerus
Short head of
biceps brachii
Long head of
biceps brachii
Brachioradialis
Pectoralis minor
Subscapularis
Teres major
Latissimus dorsi
Long head of
triceps brachii
Medial head of
triceps brachii
Brachial artery
Median nerve
Brachialis
Bicipital aponeurosis

INTRODUCTION

- Use of terms
  - Attachments
    - Origin: less moveable
    - Insertion: more moveable
  - Prime movers of a joint
    - Agonist muscle
    - Antagonistic muscles

FUNCTIONS OF MUSCLE

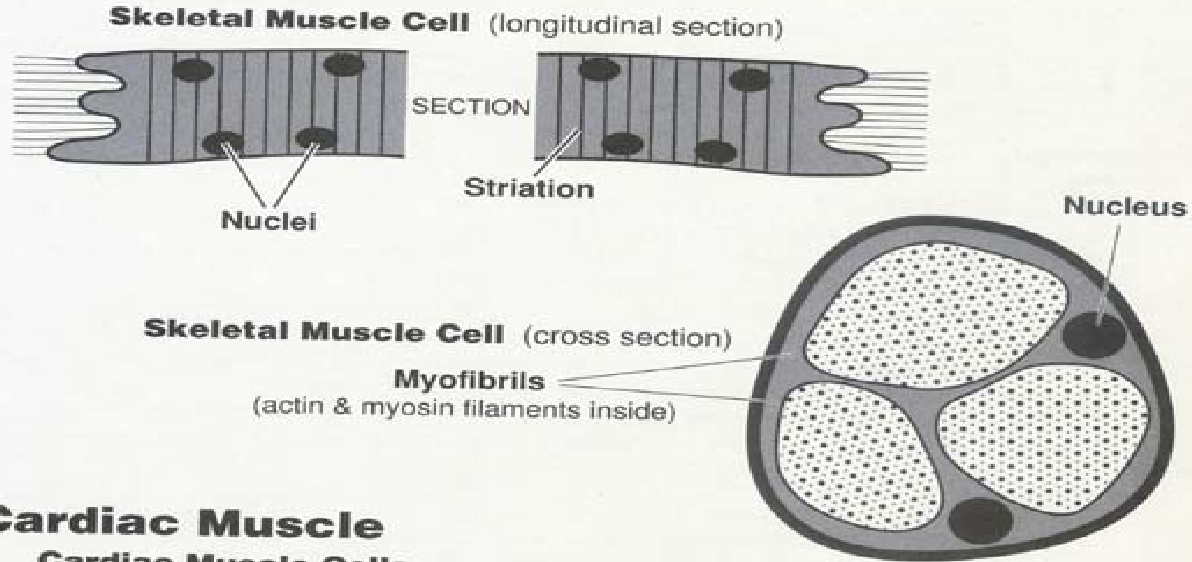
- Locomotion
- Mechanical digestion
- Propulsion
- Sphincters
- Ventilation
- Communication

TYPES OF MUSCLE

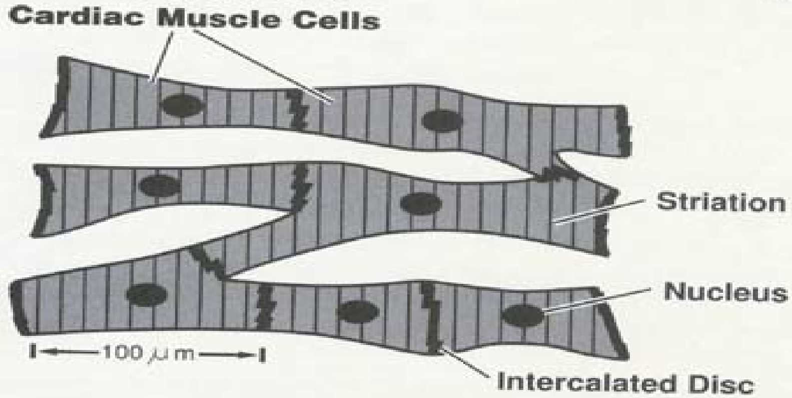
- Cardiac muscle
- Skeletal muscle
- Smooth muscle

MUSCLE TISSUES

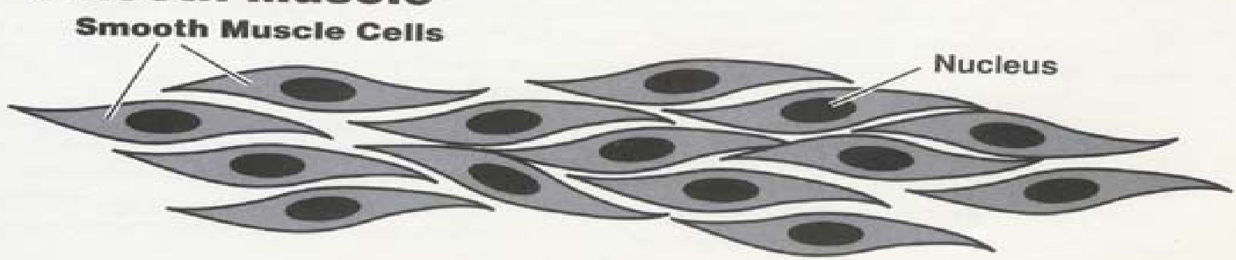
Skeletal Muscle



Cardiac Muscle



Smooth Muscle



	Used in	*Activity*	*Appearance*	*Control*	*Power*
Skeletal	Skeleton	Normally relaxed	Striated	Voluntary	High
Smooth	Hollow organs	Tonically contracting	Nonstriated	Involuntary	Low
Cardiac	Heart	Repetitively contracting	Striated	Involuntary	High

CARDIAC MUSCLE

- Similar to skeletal muscle
- Gap junctions
  - Intercalated discs
    - Spread impulses to all cells
    - All cells contract

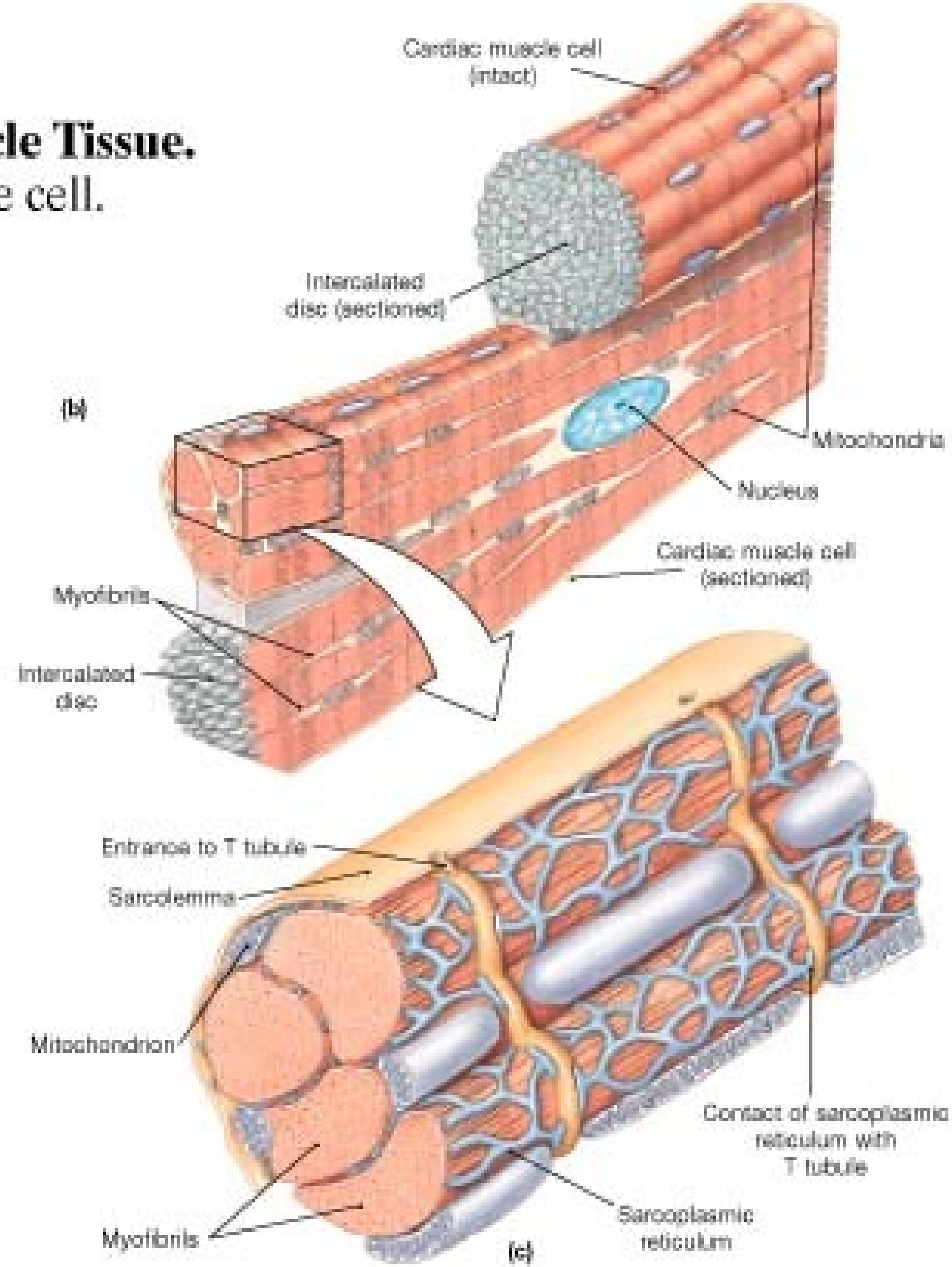
CARDIAC MUSCLE

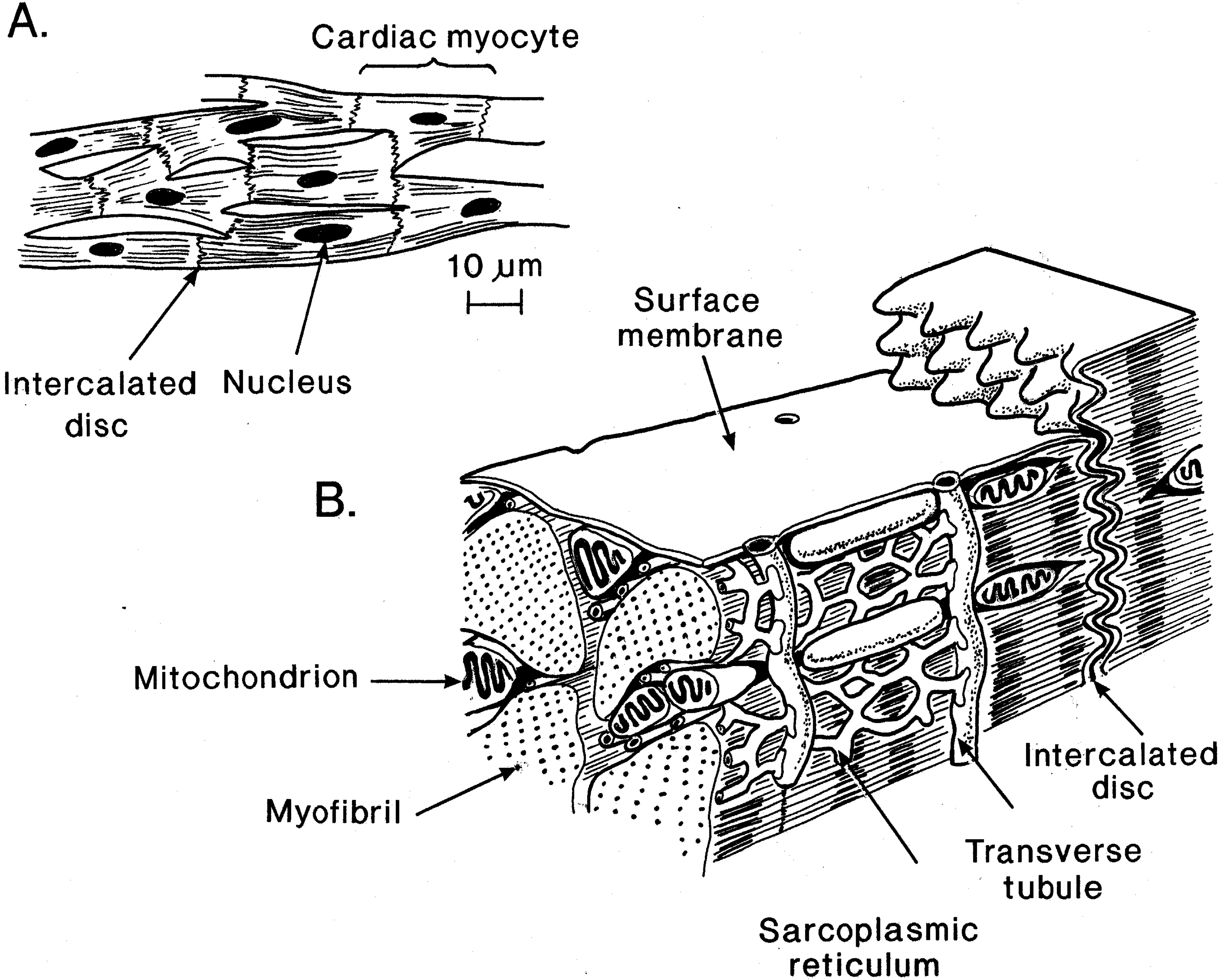
- *Location*: heart.
- *Microscopic Appearance: striated;* single nucleus; branched fibers with intercalated discs.
- *Fiber Diameter : 14* micrometers.
- *Fiber Length: 50* to 100 micrometers.

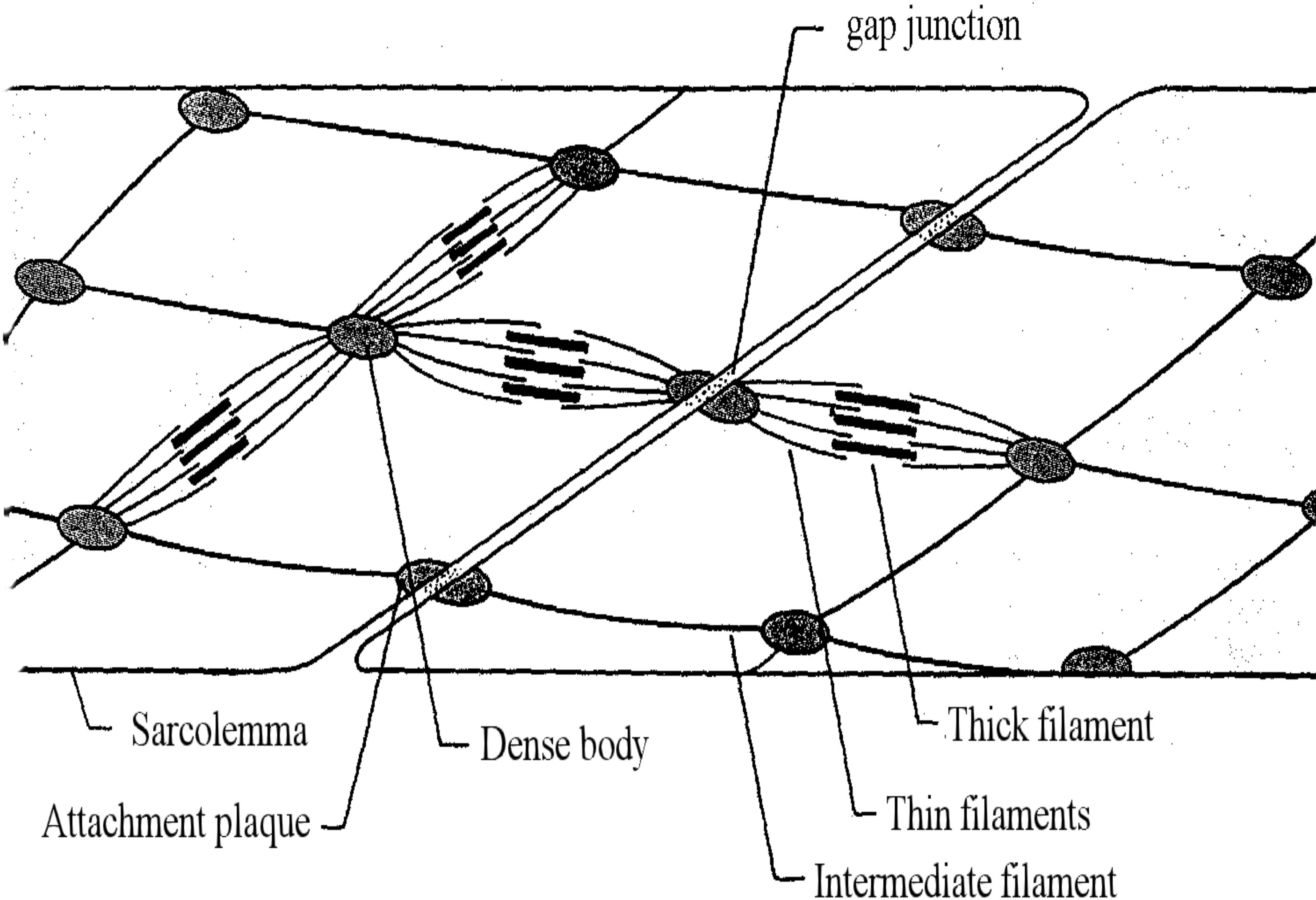
CARDIAC MUSCLE

- *Nervous Control: involuntary* (unconscious) control by autonomic nervous system.
- *Hormonal Control*: epinephrine & norepinephrine increase rate and strength of contractions.
- *Regeneration*: none.
- *Function: propels* blood through the blood vessels.

• *FIGURE 10-20* Cardiac Muscle Tissue.
(b,c) Structure of a cardiac muscle cell.




A.
Cardiac myocyte
10 µm
Intercalated disc
Nucleus
B.
Surface membrane
Mitochondrion
Myofibril
Intercalated disc
Transverse tubule
Sarcoplasmic reticulum


gap junction
Sarcolemma
Dense body
Thick filament
Attachment plaque
Thin filaments
Intermediate filament

SKELETAL MUSCLE

- *Location: attached* to bones (some attached to skin, deep fascia, or other muscles).
- *Microscopic Appearance: striated;* many nuclei in each fiber (cell); unbranched fibers.
- *Fiber Diameter: 10* to 100 micrometers.
- *Fiber Length : 100* micrometers to 30 centimeters (about 1 foot).

SKELETAL MUSCLE

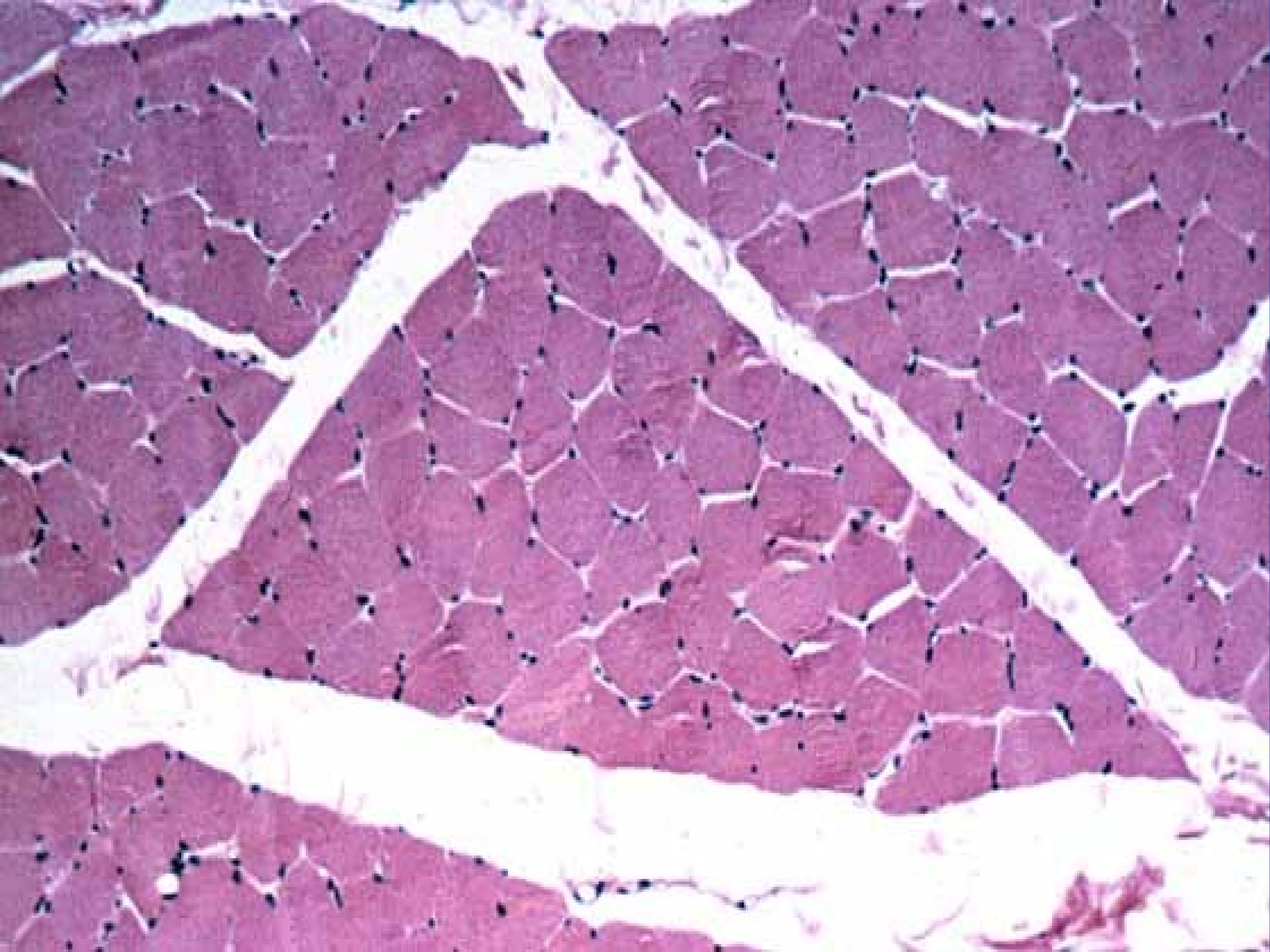
- *Nervous Control : voluntary* (conscious) control by somatic nervous system.
- *Regeneration: limited* capacity; cells cannot divide.

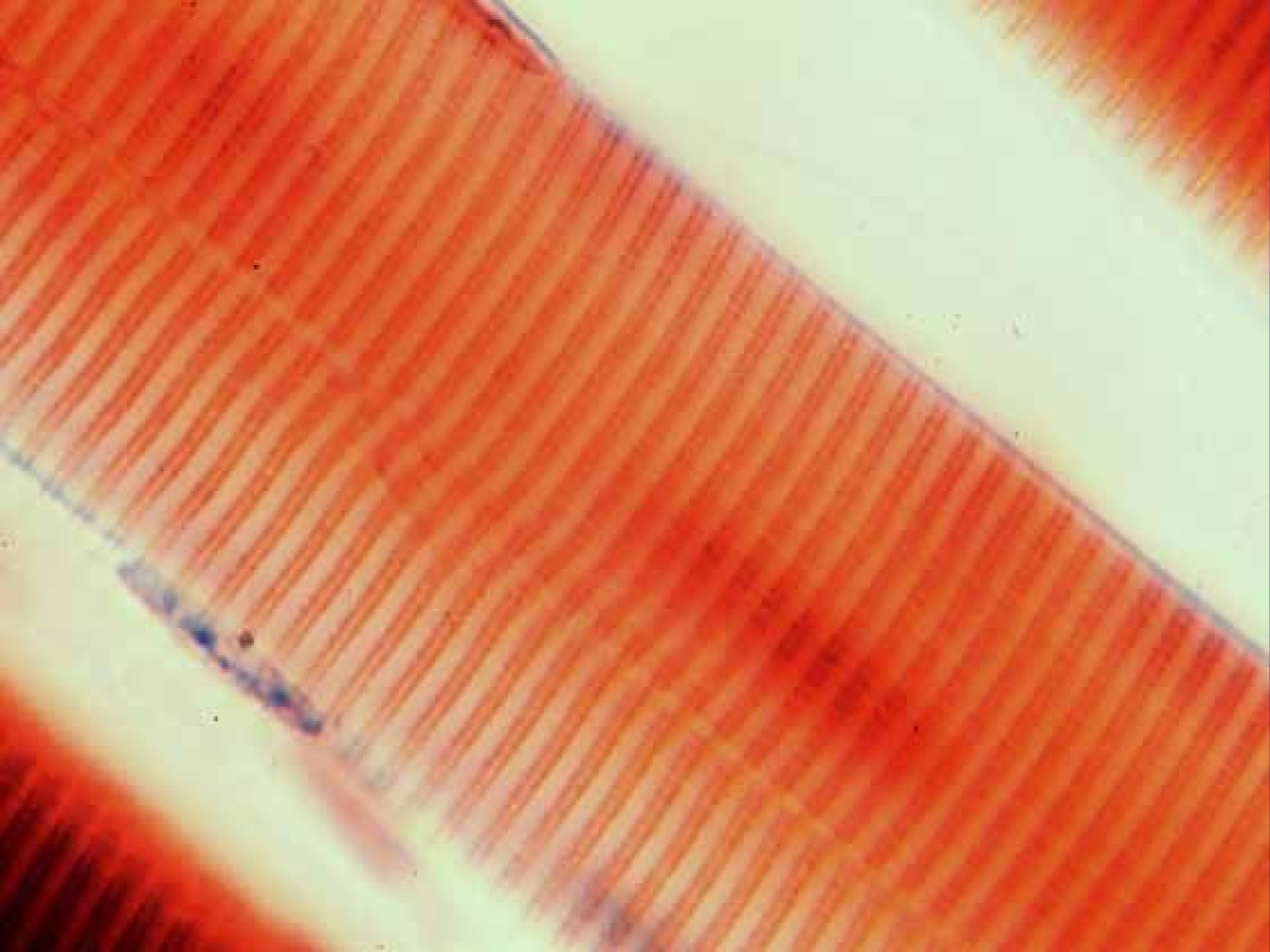
SKELETAL MUSCLE

- *Functions* moves parts of the skeleton (walking, running, nodding the head, manipulating objects);
  - postural muscles maintain the body in stable positions;
  - the diaphragm regulates breathing by changing intrathoracic volume.

SKELETAL MUSCLE

- Functional units
  - Named muscles
    - **Muscle fascicles**
      - Mu**scle fibers**
        - **Myofibrils**
          - **Myofilaments**
            - **Striations**



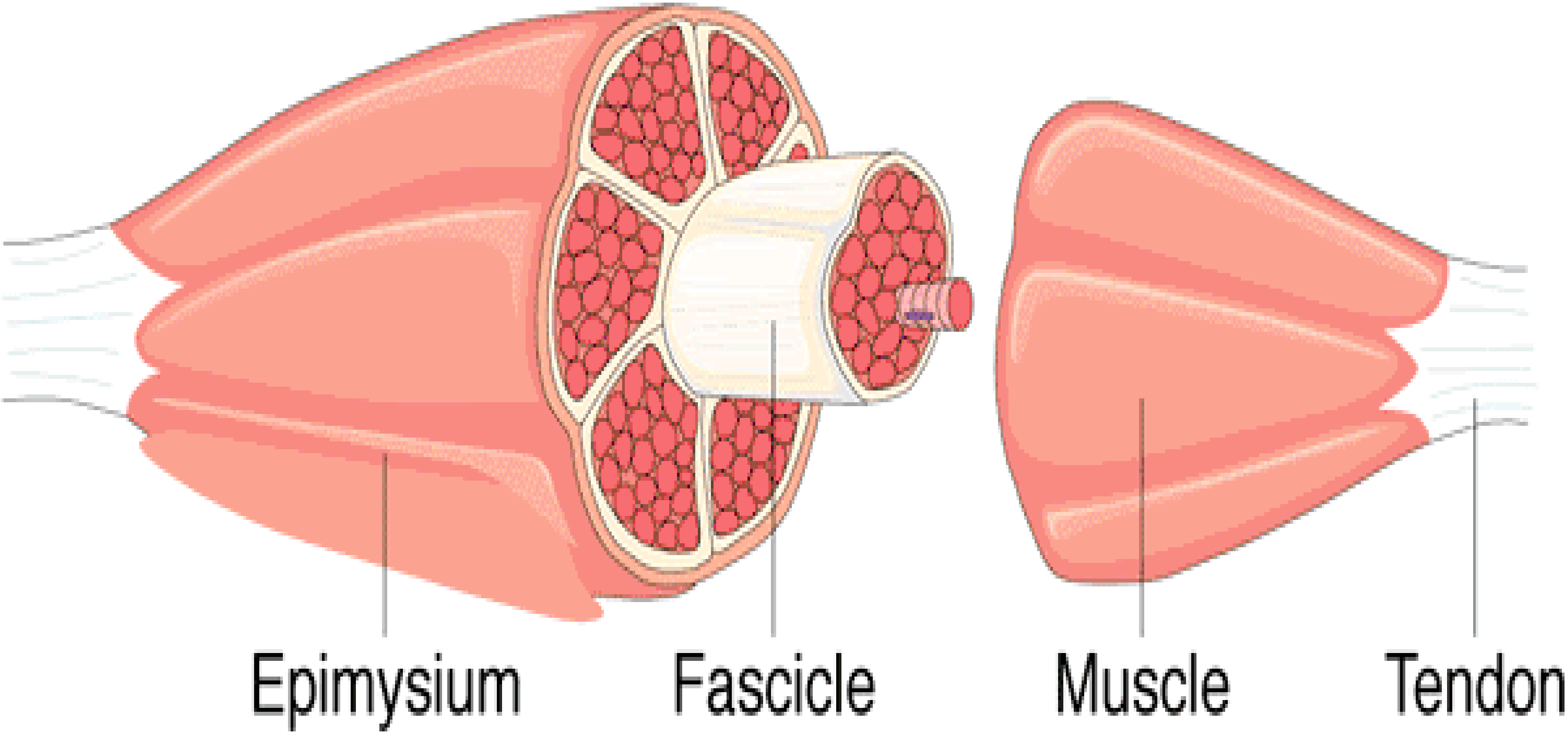


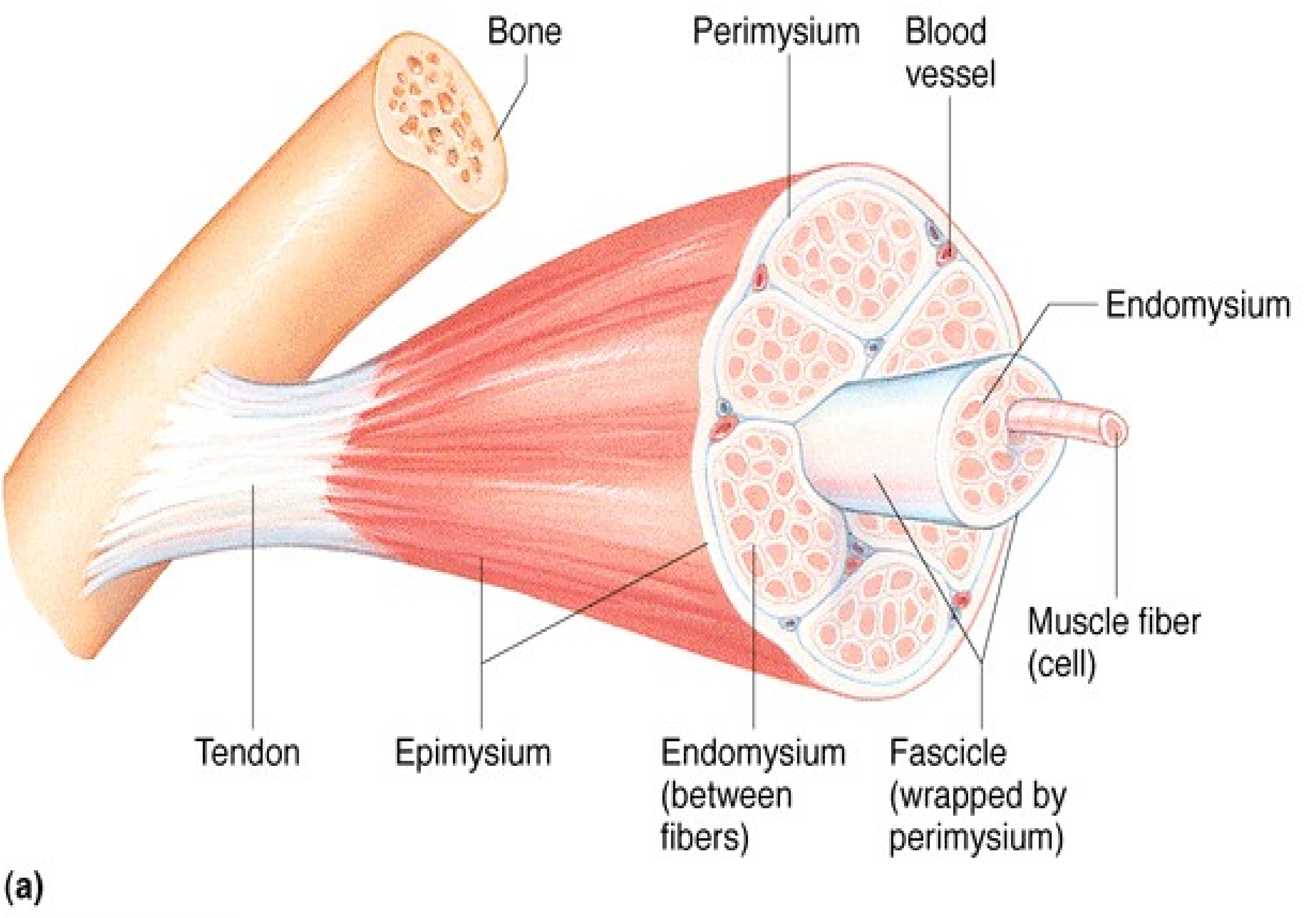
STRUCTURE OF SKELETAL MUSCLE

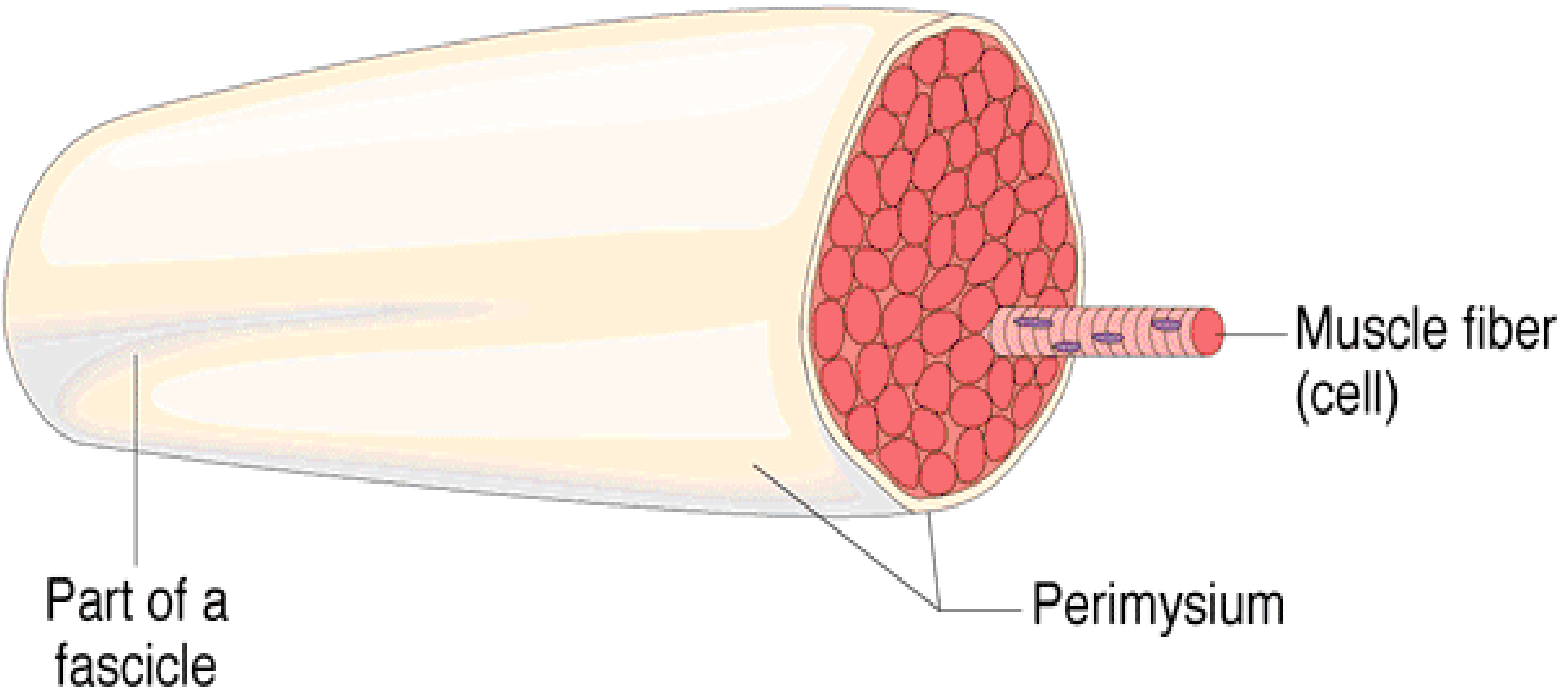
- At the LM level
  - Alternating light and dark bands
    - Light: isotrophic bands
    - Dark: anisotrophic bands

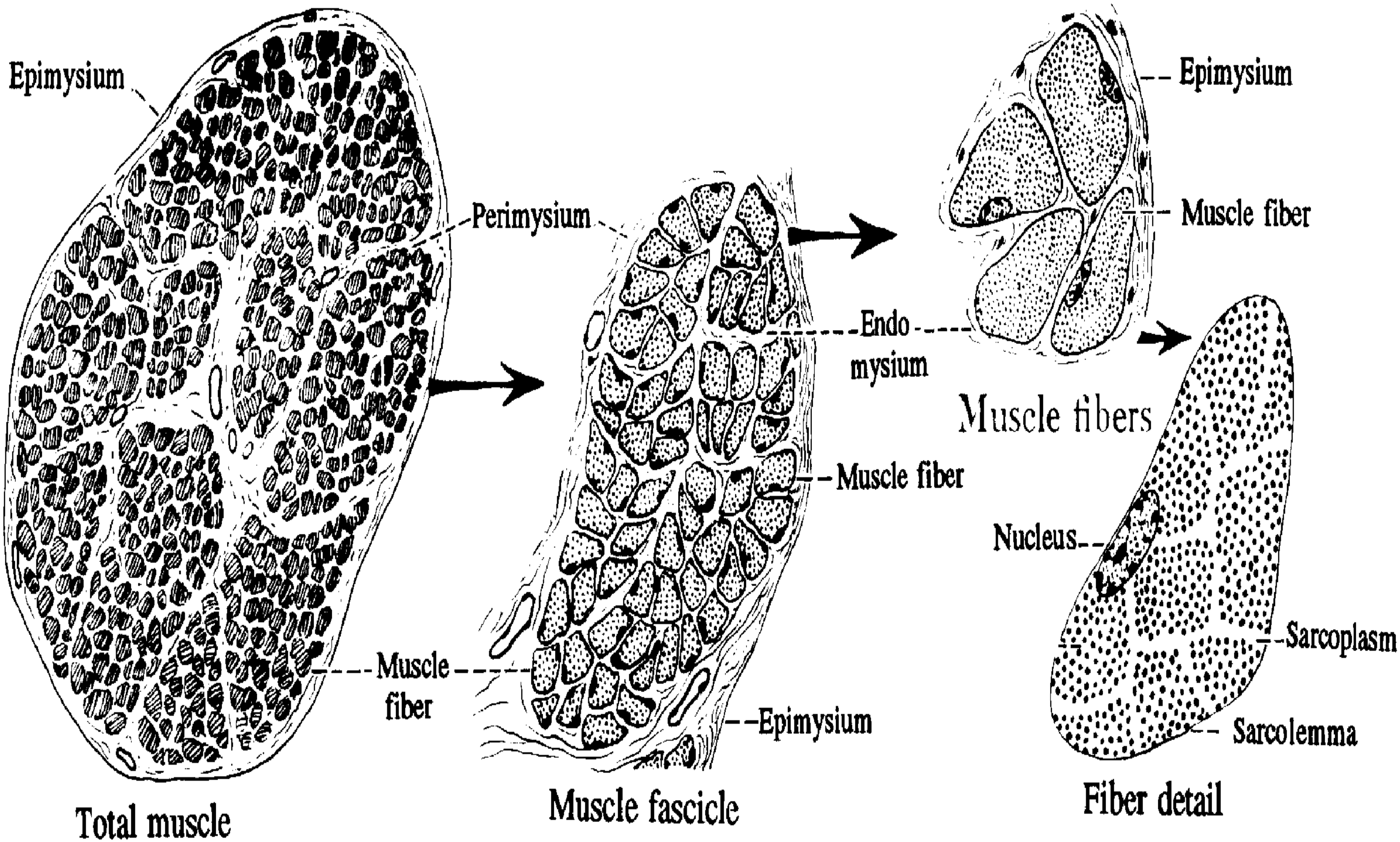
CONNECTIVE TISSUE ELEMENTS OF SKELETAL MUSCLE

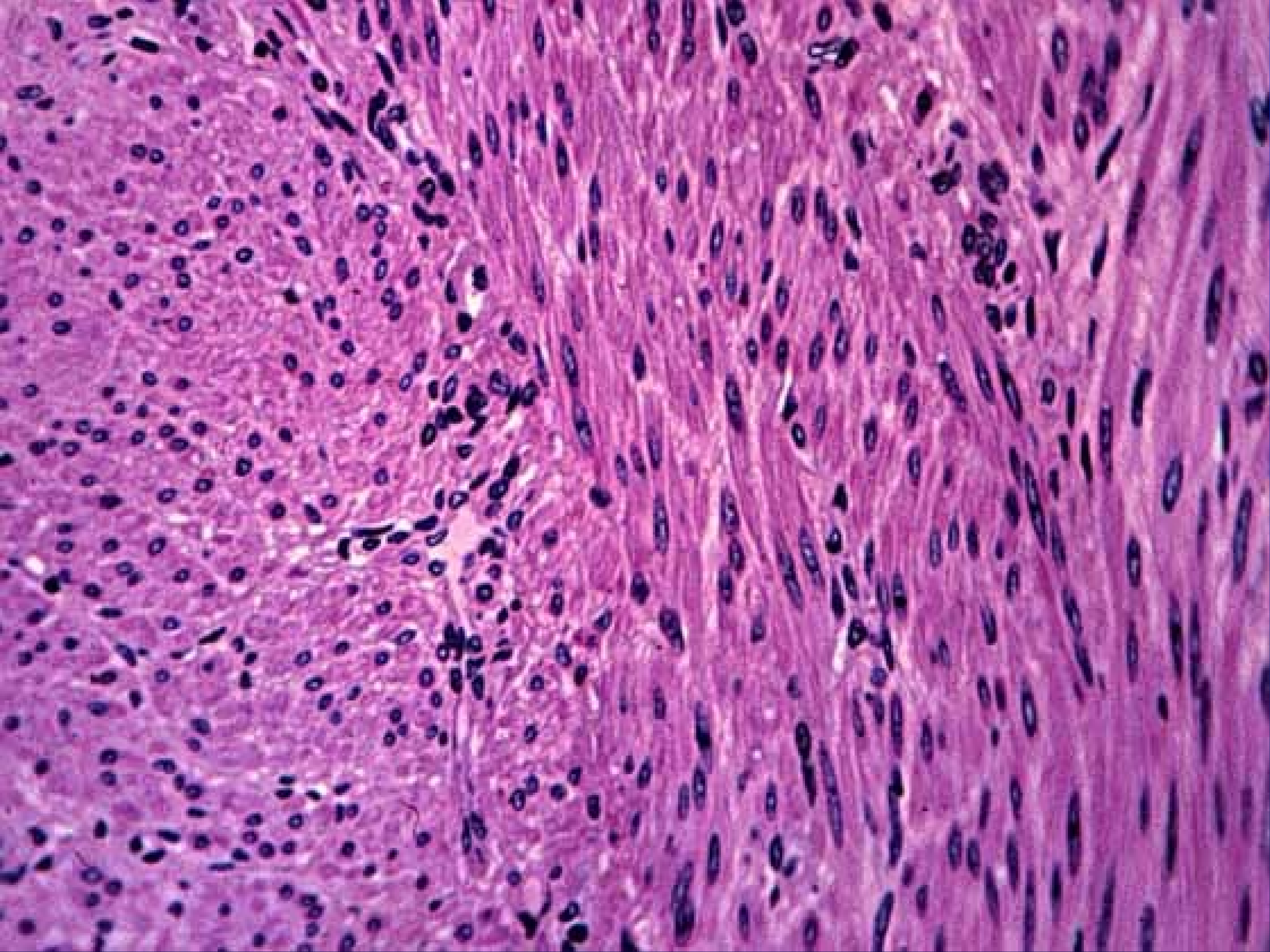
- Epimysium
- Perimysium
- Endomysium

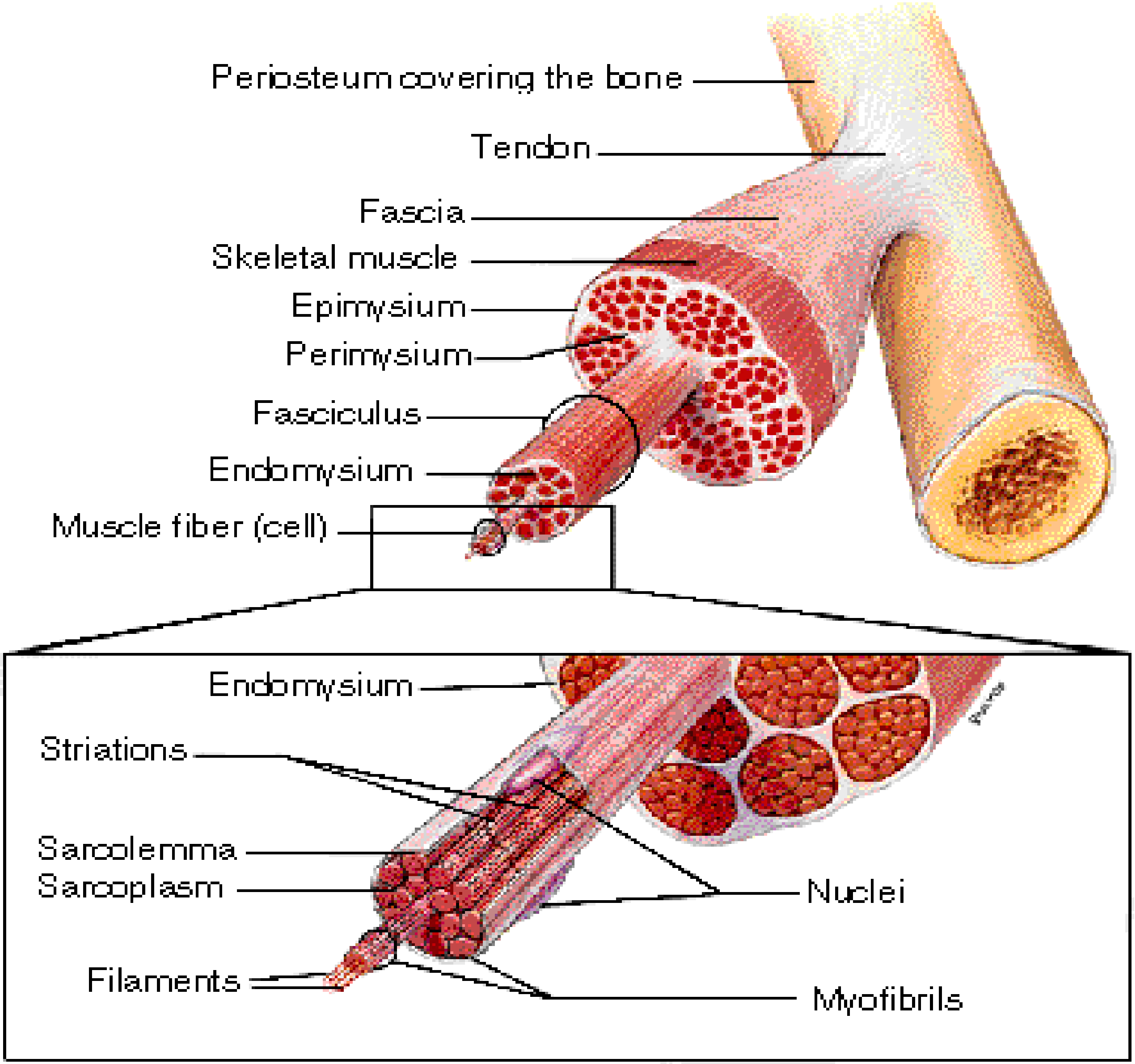

Epimysium
Fascicle
Muscle
Tendon


Bone
Perimysium
Blood vessel
Endomysium
Muscle fiber (cell)
Tendon
Epimysium
Endomysium (between fibers)
Fascicle (wrapped by perimysium)
(a)


Muscle fiber
(cell)
Part of a
fascicle
Perimysium


Epimysium
Perimysium
Muscle fiber
Total muscle
Muscle fiber
Epimysium
Muscle fascicle
Epimysium
Muscle fiber
Endo mysium
Muscle fibers
Nucleus
Sarcoplasm
Sarcolemma
Fiber detail

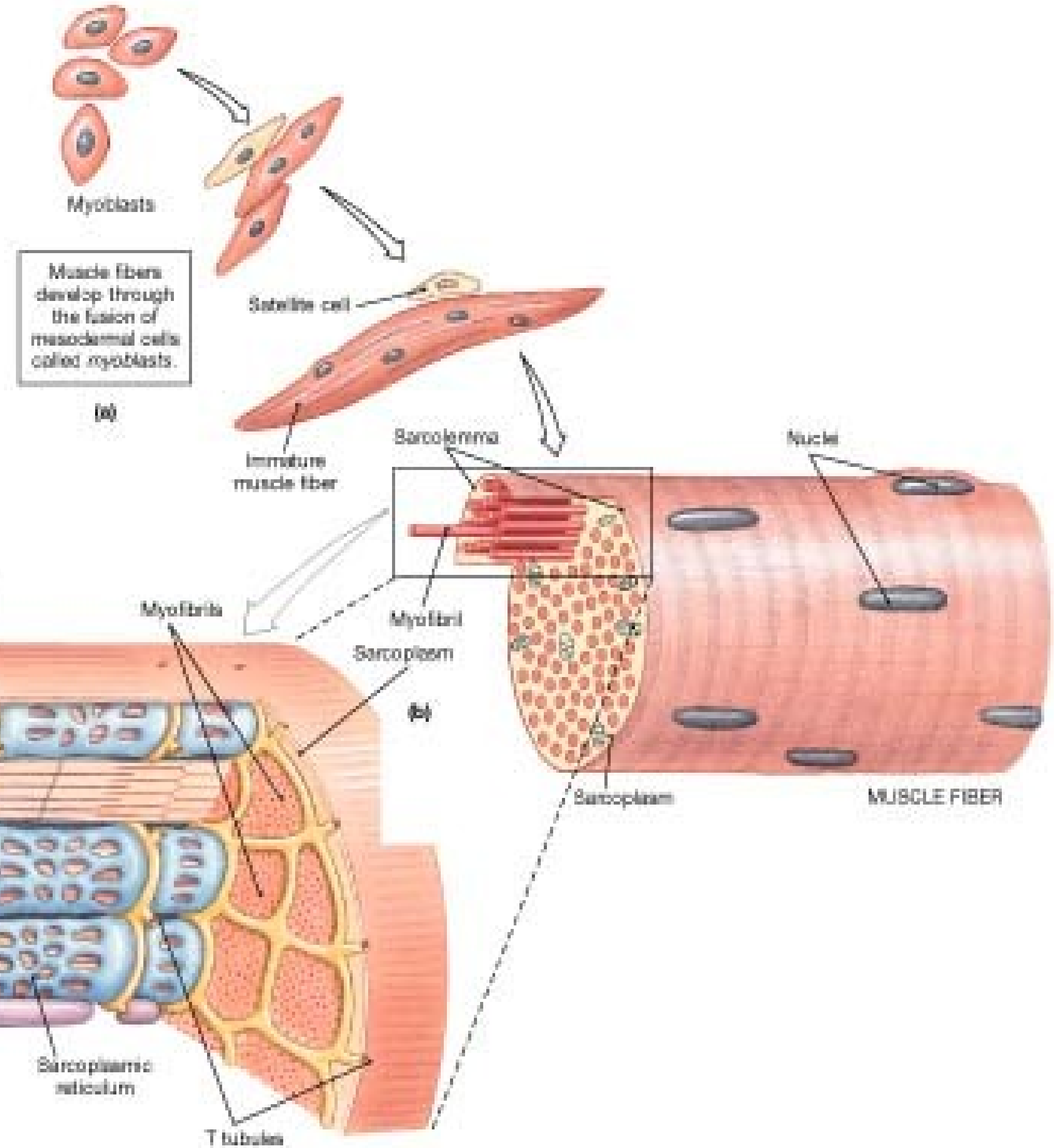



Periosteum covering the bone
Tendon
Fascia
Skeletal muscle
Epimysium
Perimysium
Fasciculus
Endomysium
Muscle fiber (cell)
Endomysium
Striations
Sarcolemma
Sarcoplasm
Filaments
Nuclei
Myofibrils

Development of Muscle Fibers

- Fusion of Myoblast
- Satellite cells

• ***FIGURE 10-2*** **Formation and Structure of a Skeletal Muscle Fiber.** **(a)** The formation of muscle fibers through the fusion of myoblasts. **(b)** Diagrammatic view of one muscle fiber. **(c)** The internal organization of a muscle fiber.



CELL STRUCTURE

- Characteristics of skeletal muscle fibers

COMPONENTS

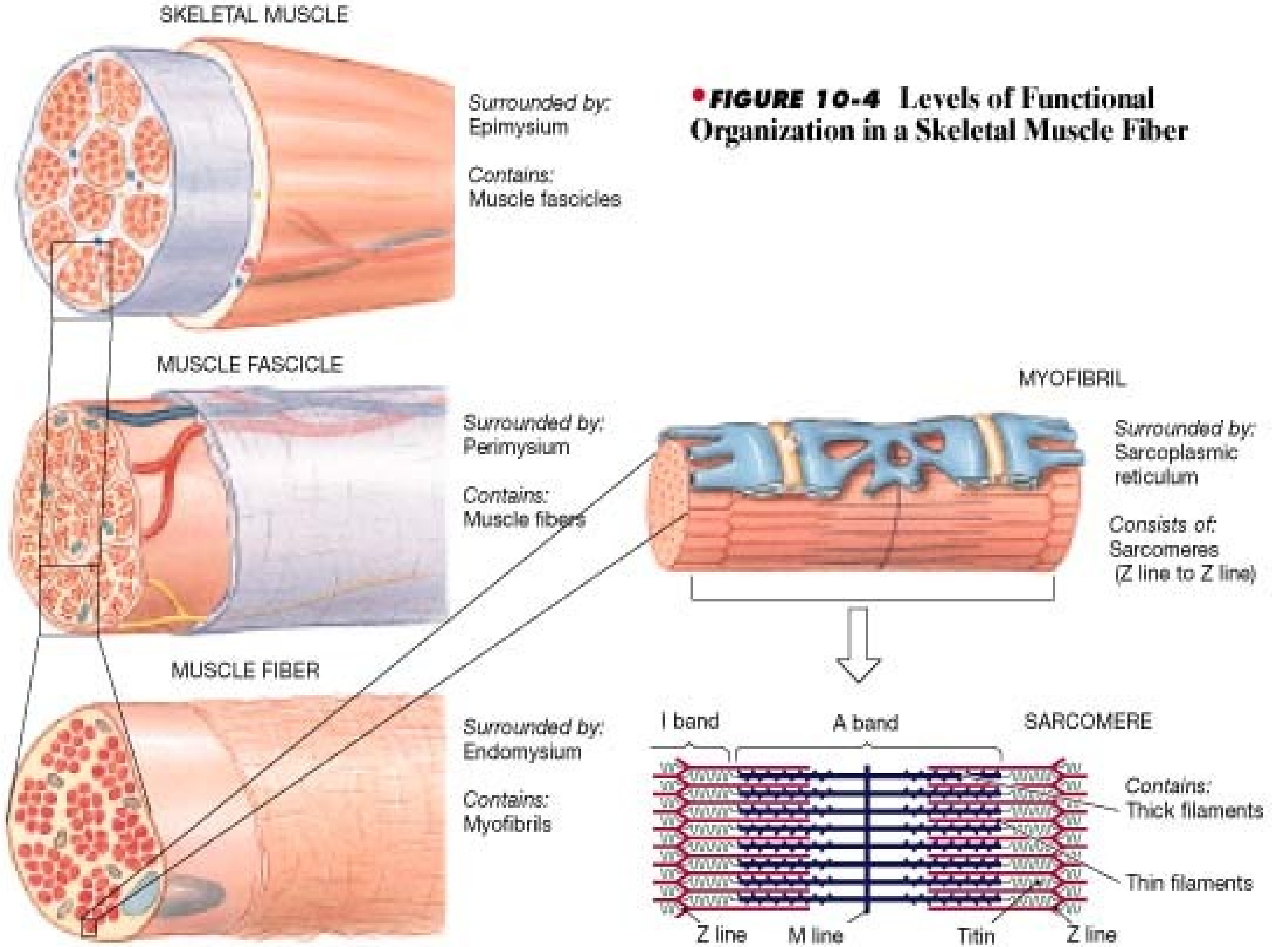
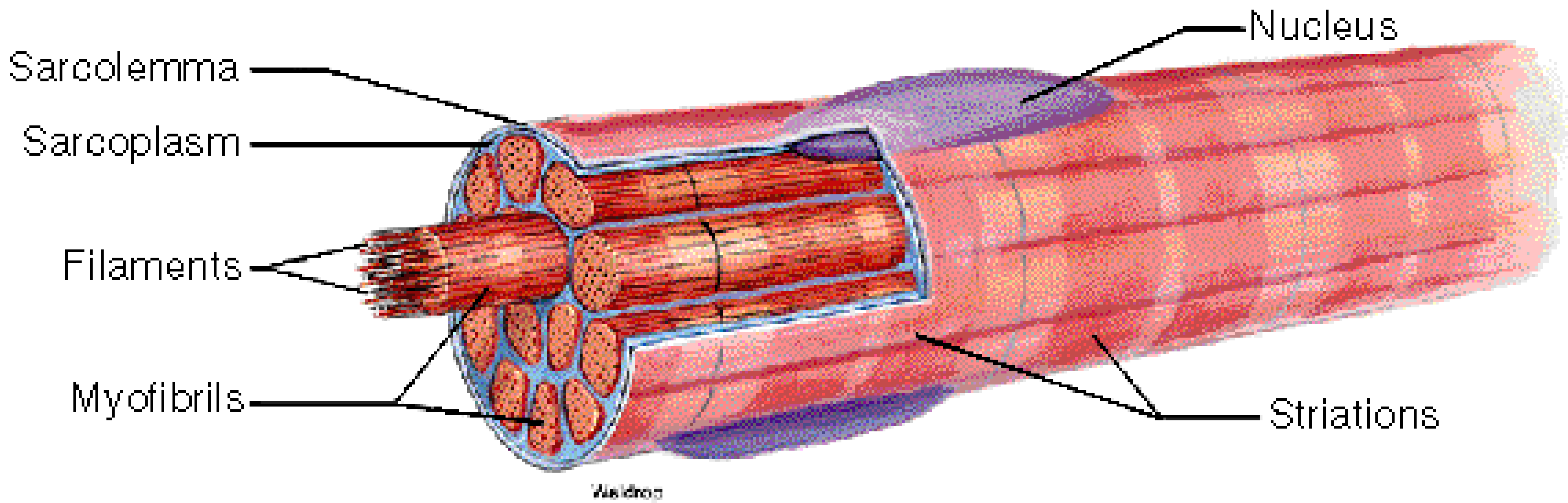
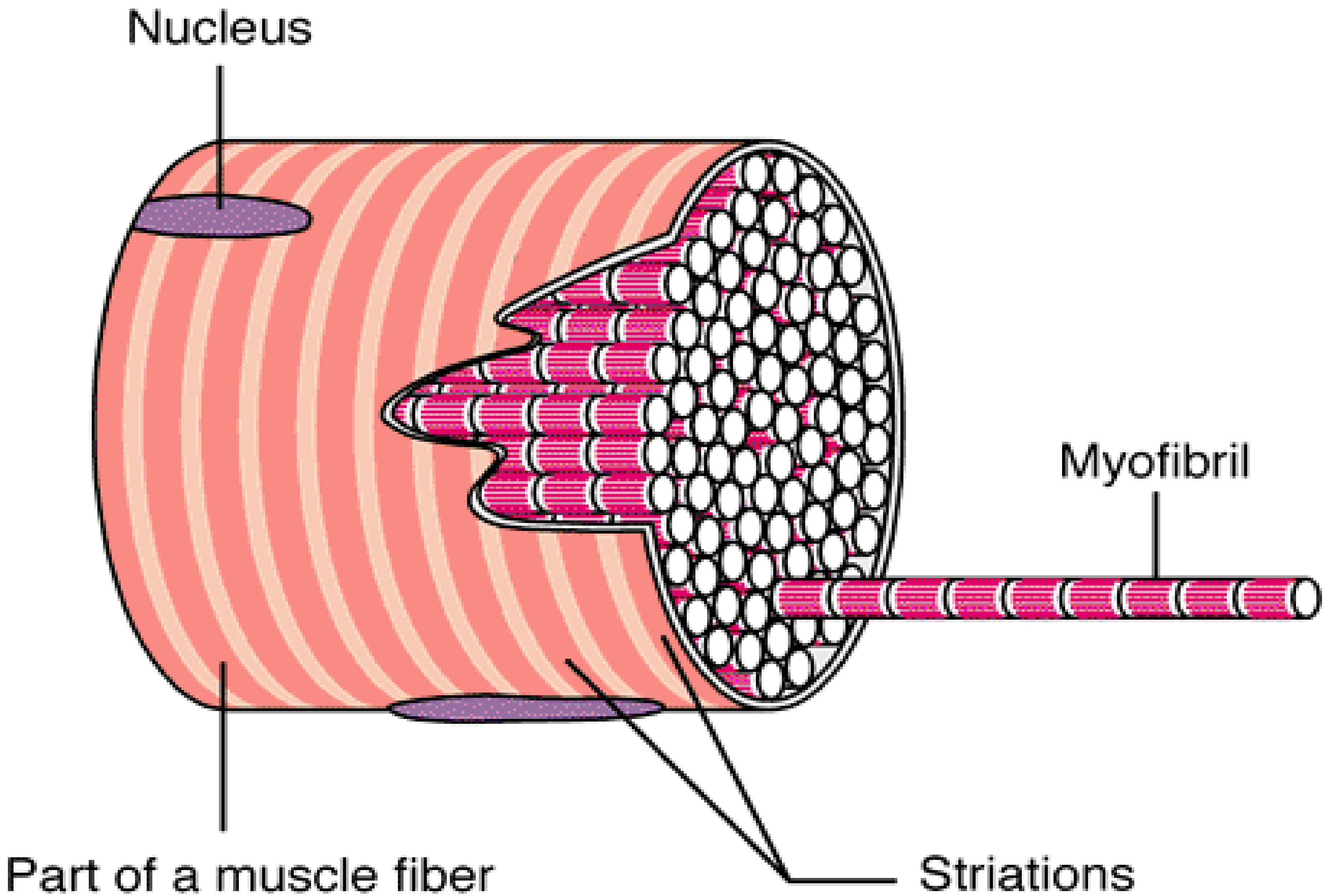
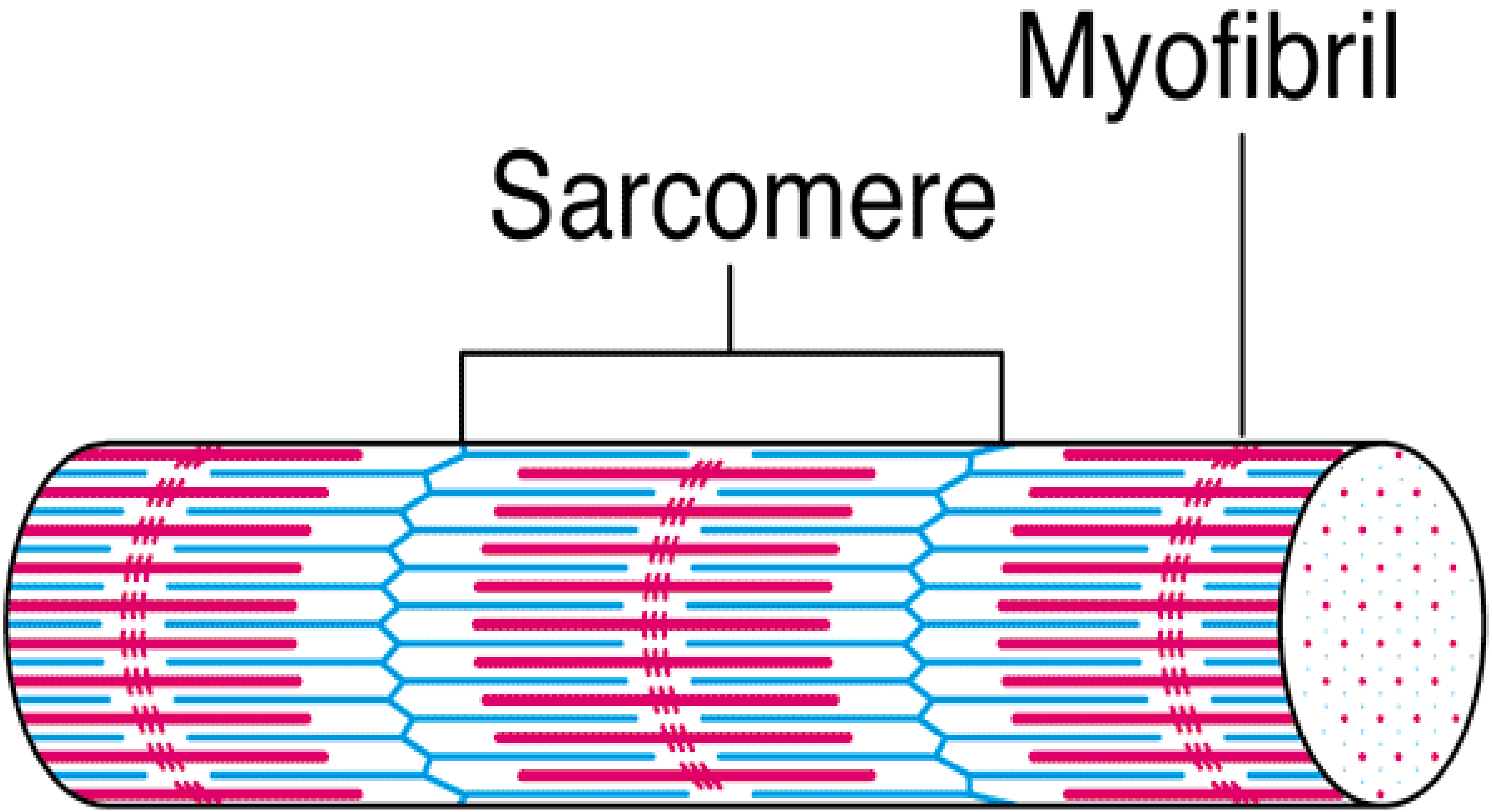


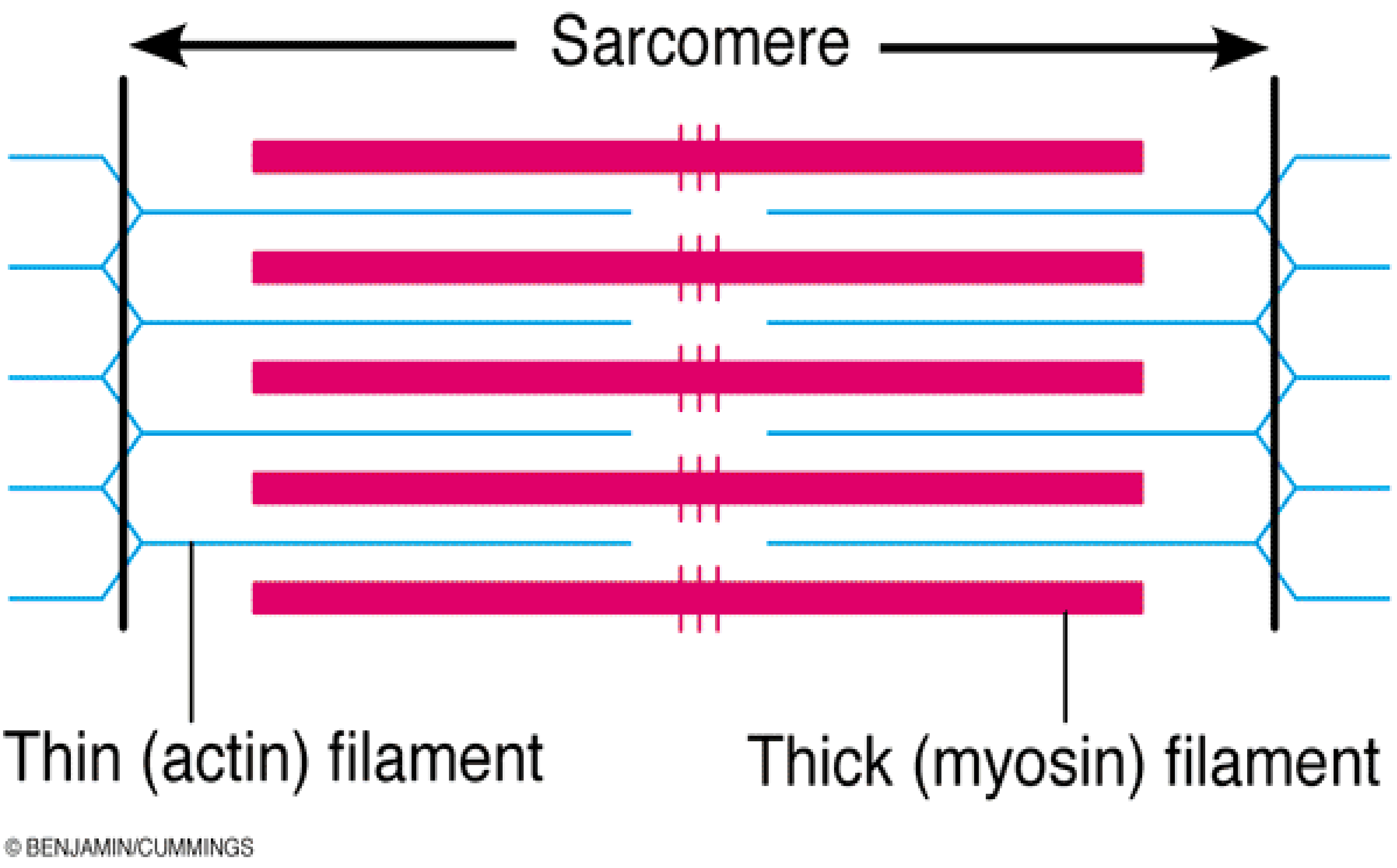
FIGURE 10-4 Levels of Functional Organization in a Skeletal Muscle Fiber

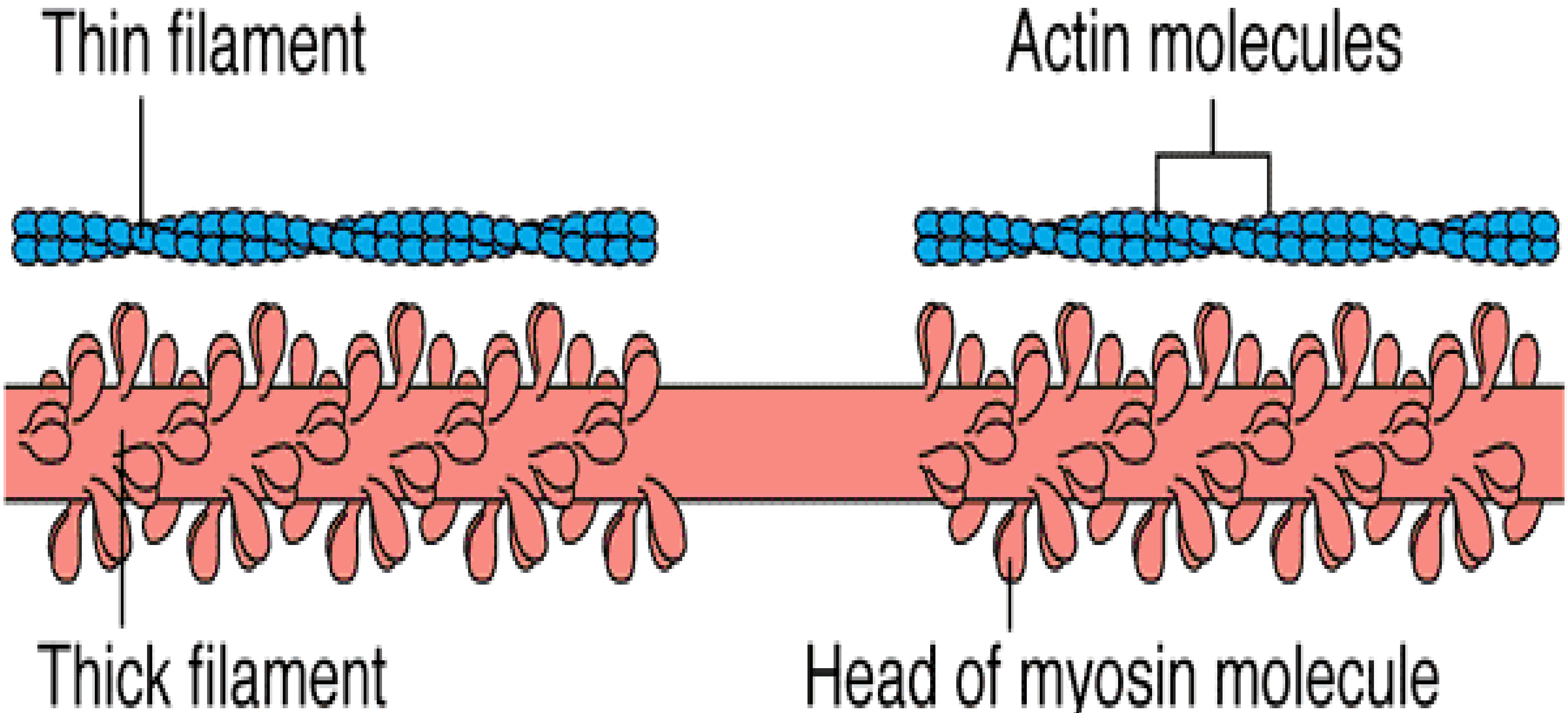
Skeletal Muscle Fiber. Figure 12.8



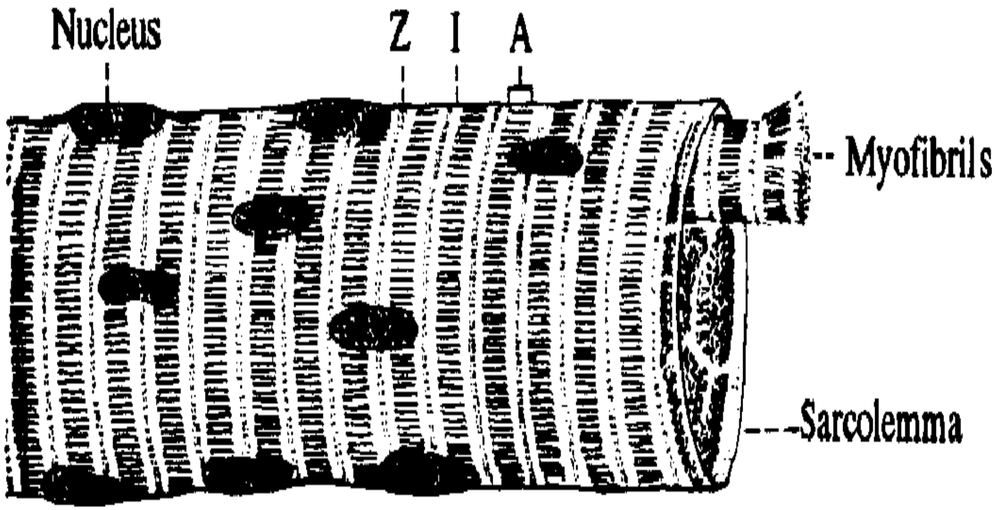

Nucleus
Myofibril
Part of a muscle fiber
Striations


Myofibril
Sarcomere

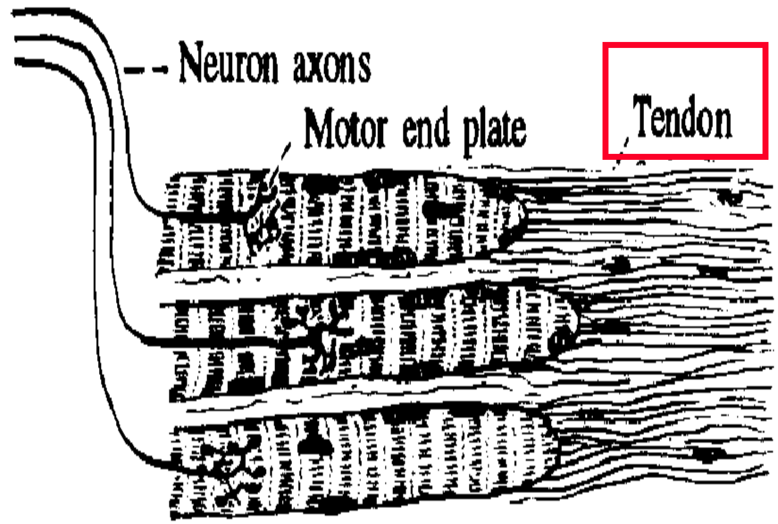

Sarcomere
Thin (actin) filament
Thick (myosin) filament
© BENJAMIN/CUMMINGS


Thin filament
Actin molecules
Thick filament
Head of myosin molecule

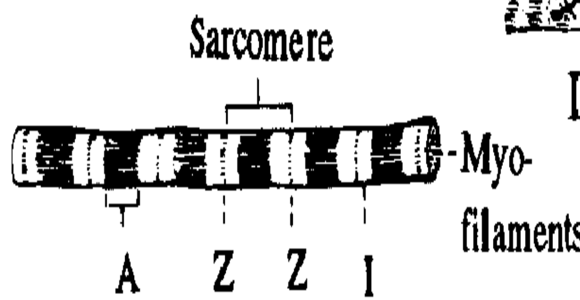
Isolated skeletal muscle fiber



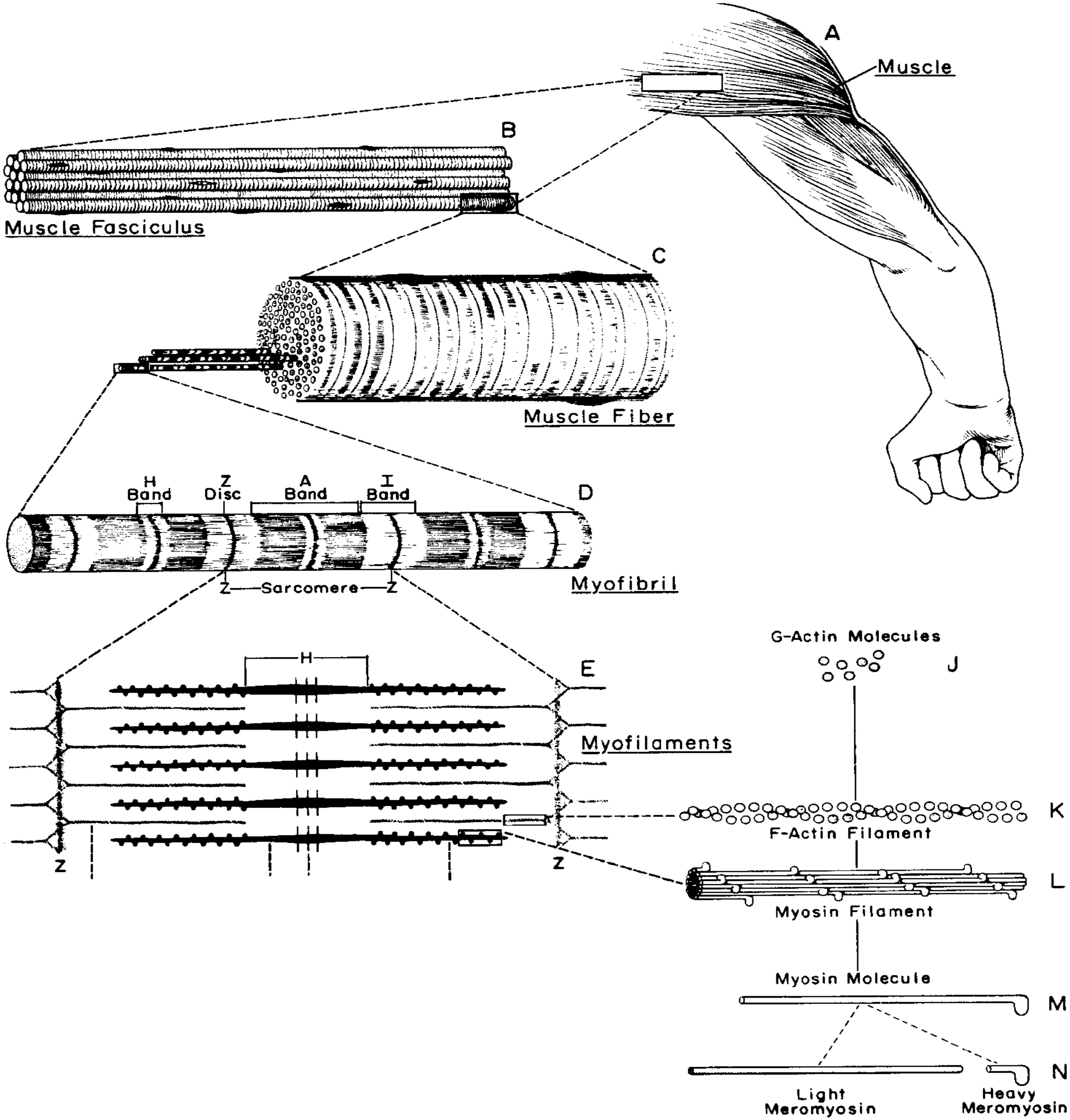
Fiber detail



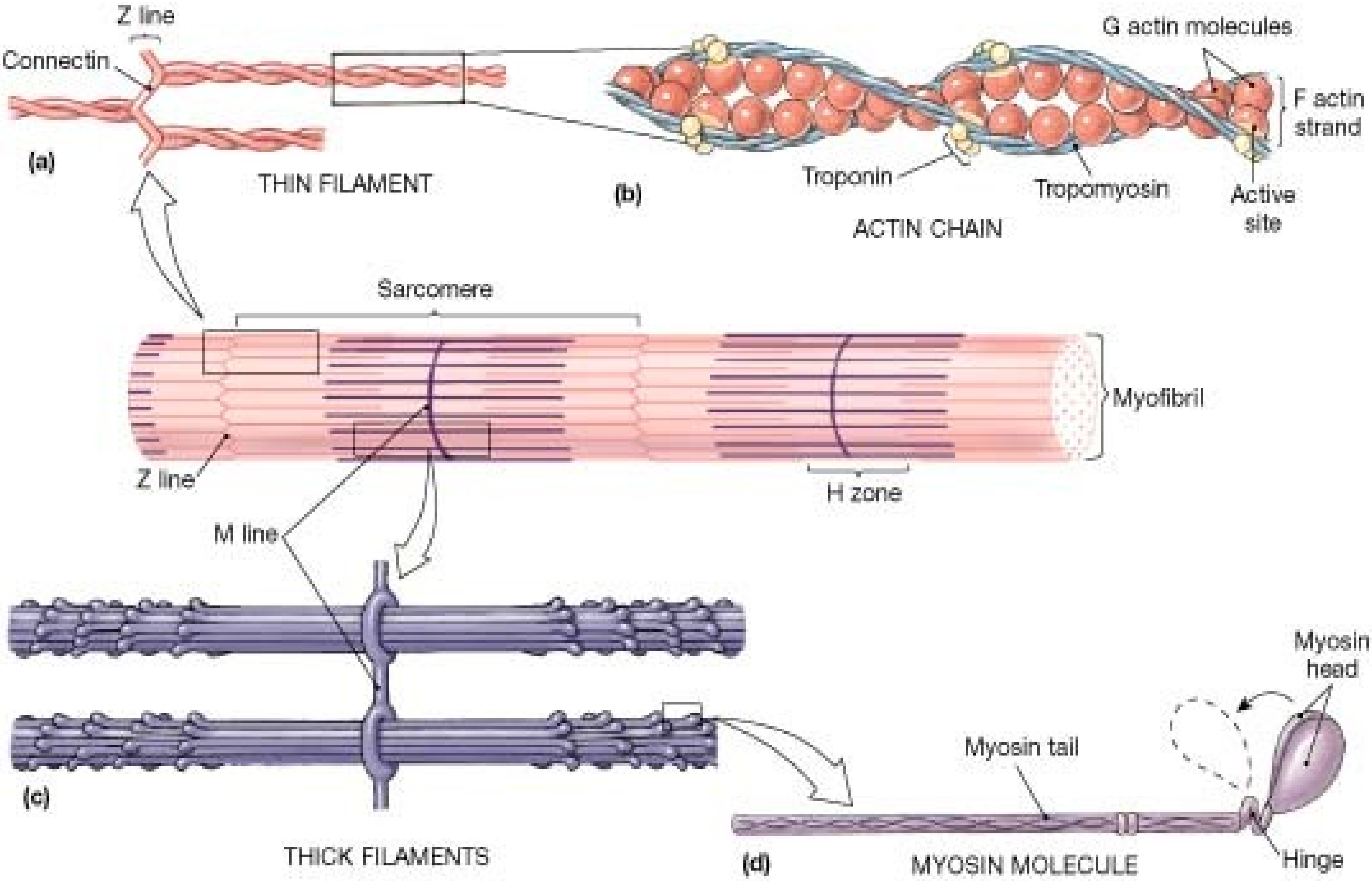
Innervation and ending



Fibril detail


A
Muscle
B
Muscle Fasciculus
C
Muscle Fiber
H Band
Z Disc
A Band
I Band
D
Myofibril
Z
Sarcomere
Z
H
E
Myofilaments
Z
Z
G-Actin Molecules
J
K
F-Actin Filament
L
Myosin Filament
Myosin Molecule
M
N
Light Meromyosin
Heavy Meromyosin

STRUCTURE OF SARCOMERE



• ***FIGURE 10-5*** **Thick and Thin Filaments.** **(a)** Gross structure of a thin filament, showing the attachment at the Z line. **(b)** The organization of G actin subunits in an F actin strand and the position of the troponin–tropomyosin complex. **(c)** Structure of a thick filament, showing the orientation of the myosin molecules along the thick filaments. **(d)** Structure of a myosin molecule.

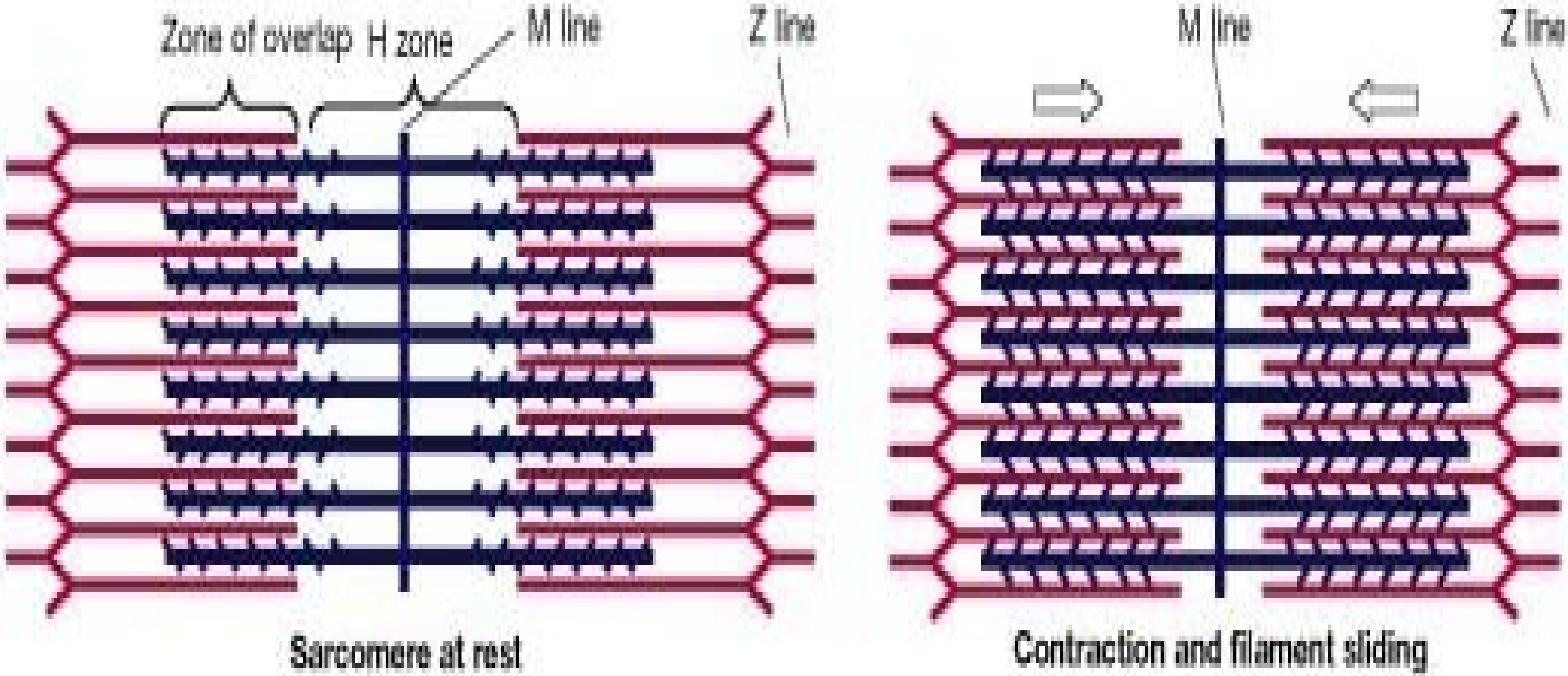


FIGURE 10-6 Changes in the Appearance of a Sarcomere during Contraction of a Skeletal Muscle Fiber. During a contraction, the A band stays the same width, but the Z lines move closer together and the I band gets smaller. For clarity, titin fibers are not shown.

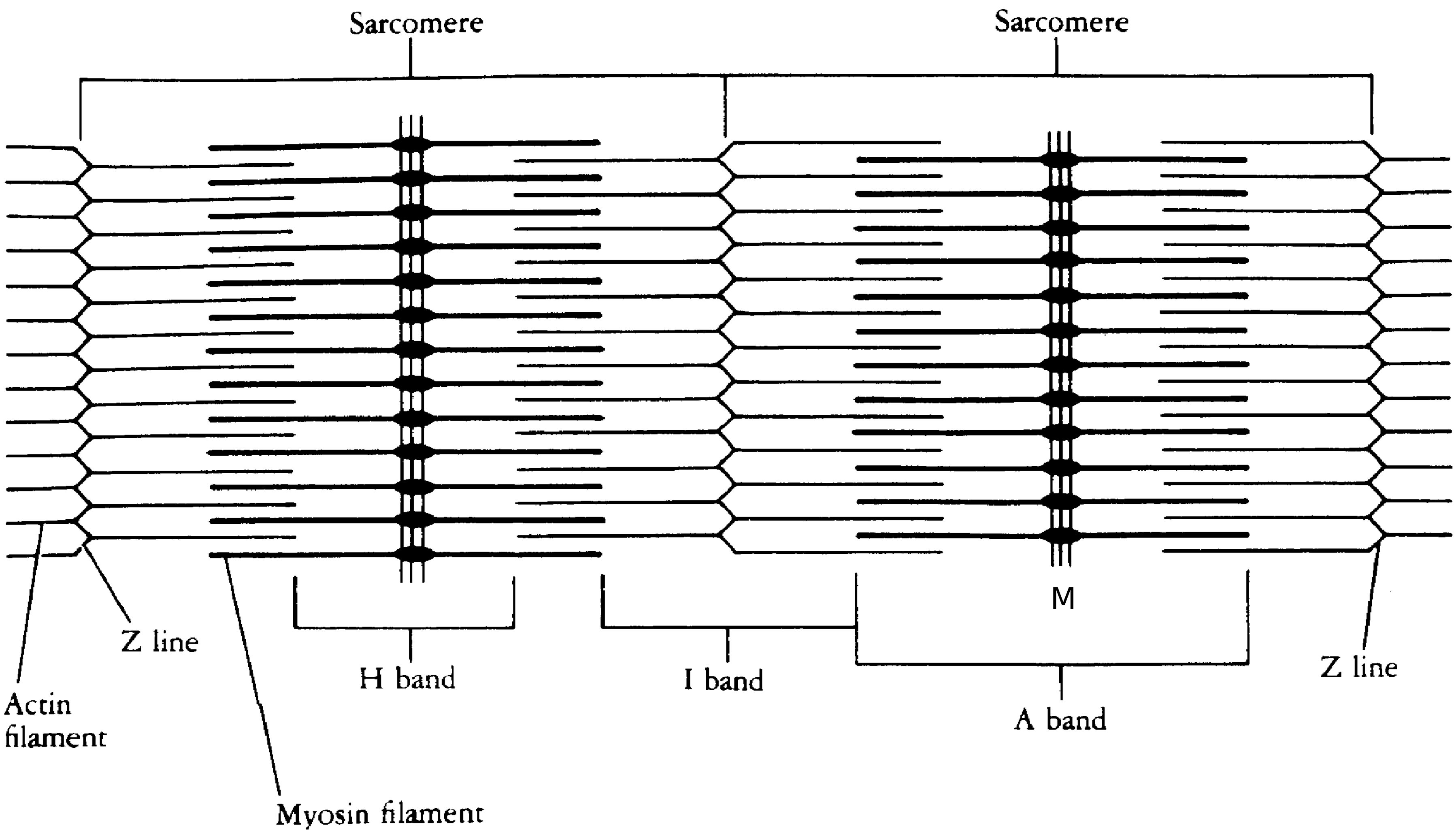
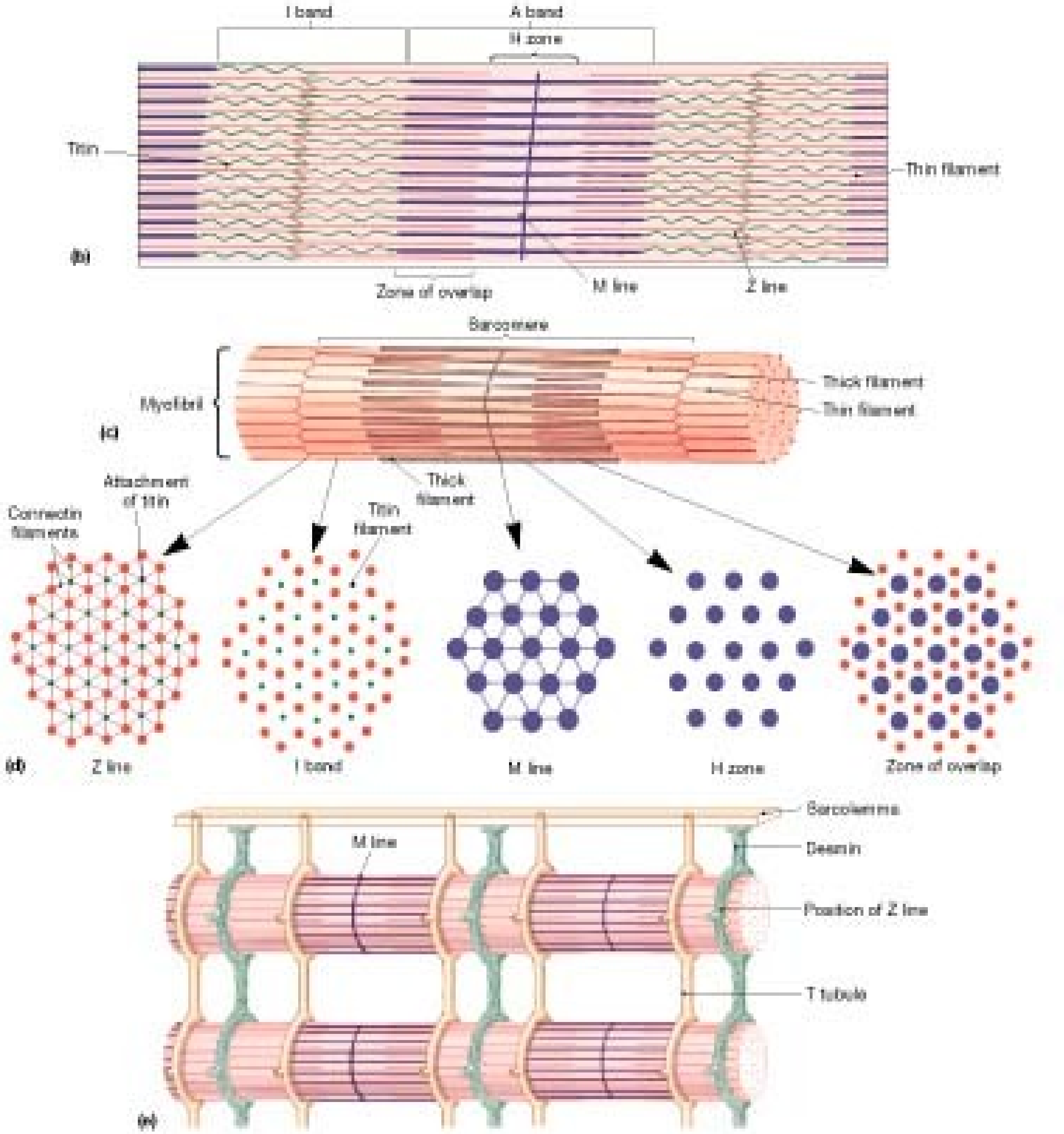
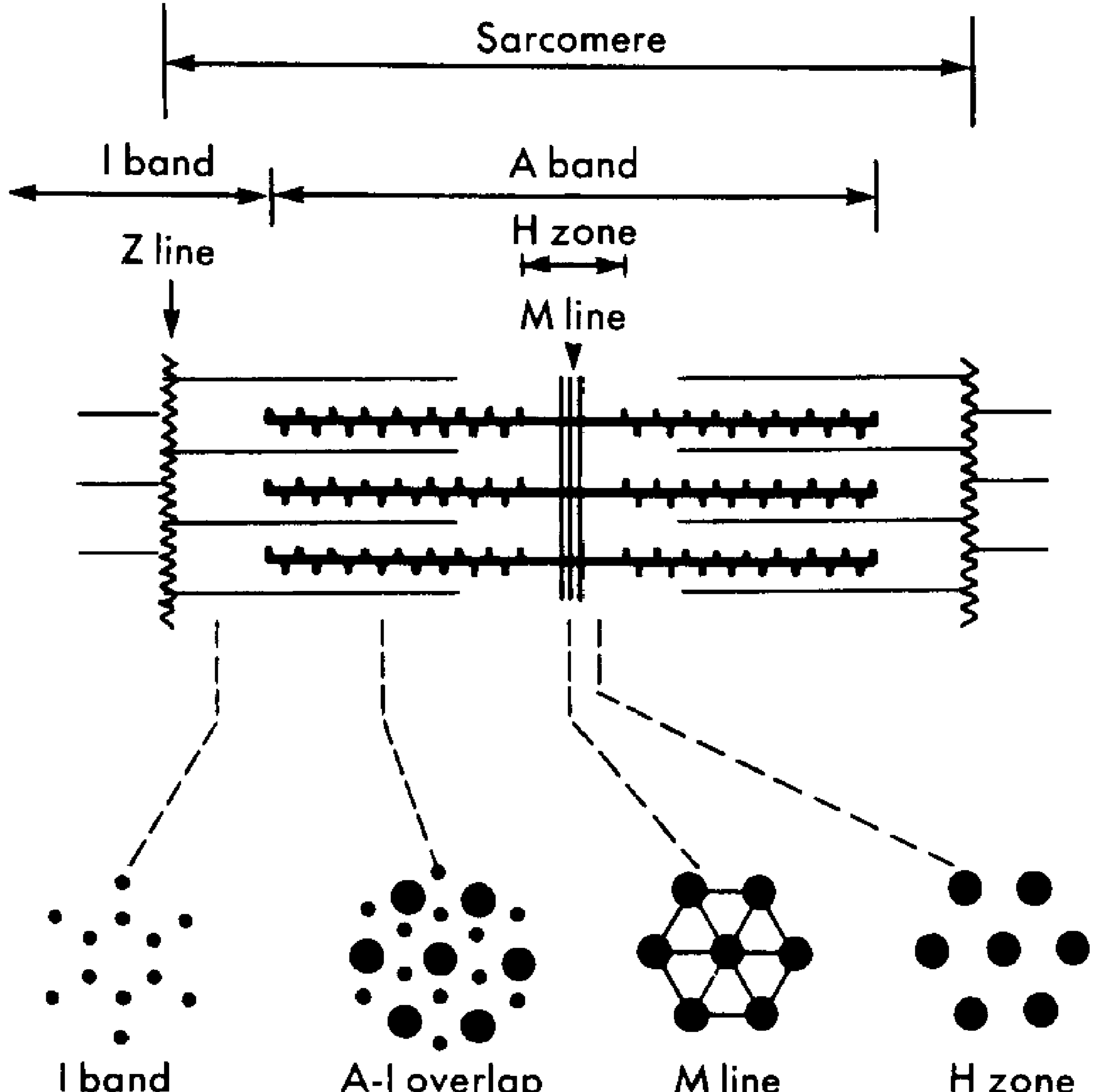

Sarcomere
Sarcomere
M
Z line
H band
I band
Z line
A band
Actin filament
Myosin filament

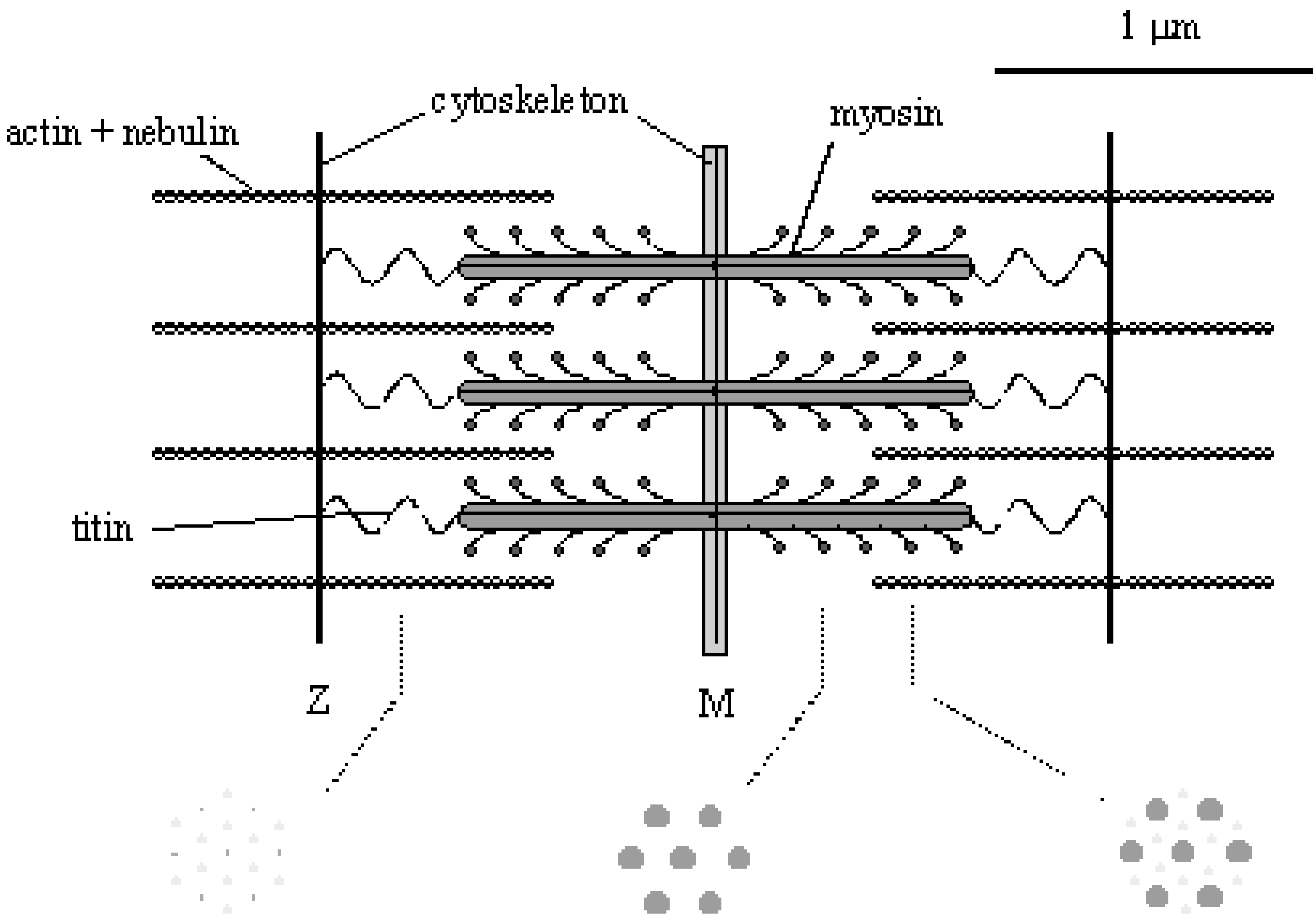
FIGURE 10-3 Sarcomere Structure. **(b)** Simplified diagrammatic view of a sarcomere. **(c)** Organization of thick and thin filaments in a sarcomere. **(d)** Cross-sectional views of different portions of the sarcomere. **(e)** The organization of the cytoskeleton, which maintains the alignment of sarcomeres and myofibrils within the muscle fiber. The interconnections extend to the myofibrils on both sides.



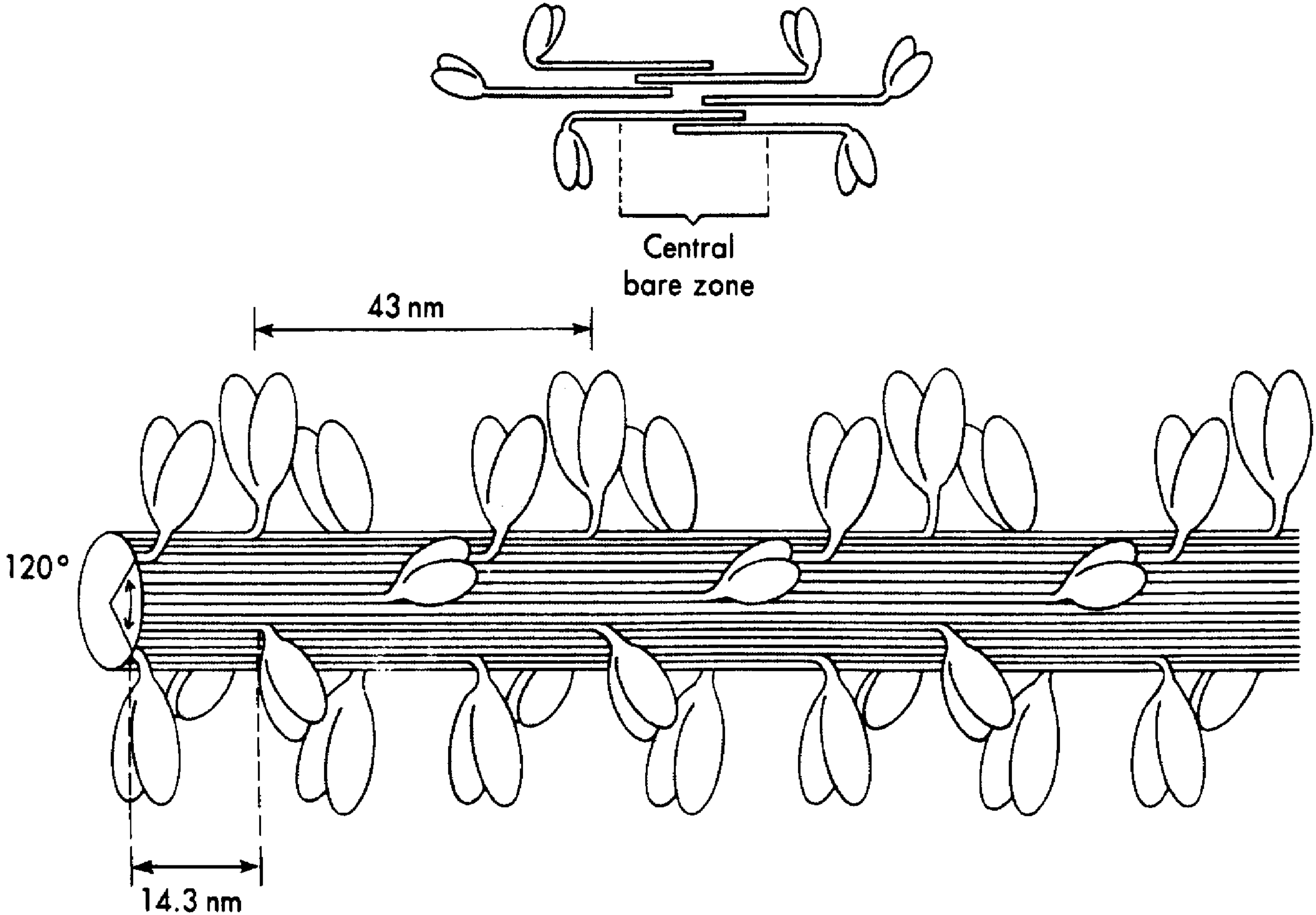


Sarcomere
I band
A band
H zone
Z line
M line
I band
A-I overlap
M line
H zone

Structure of a Sarcomere

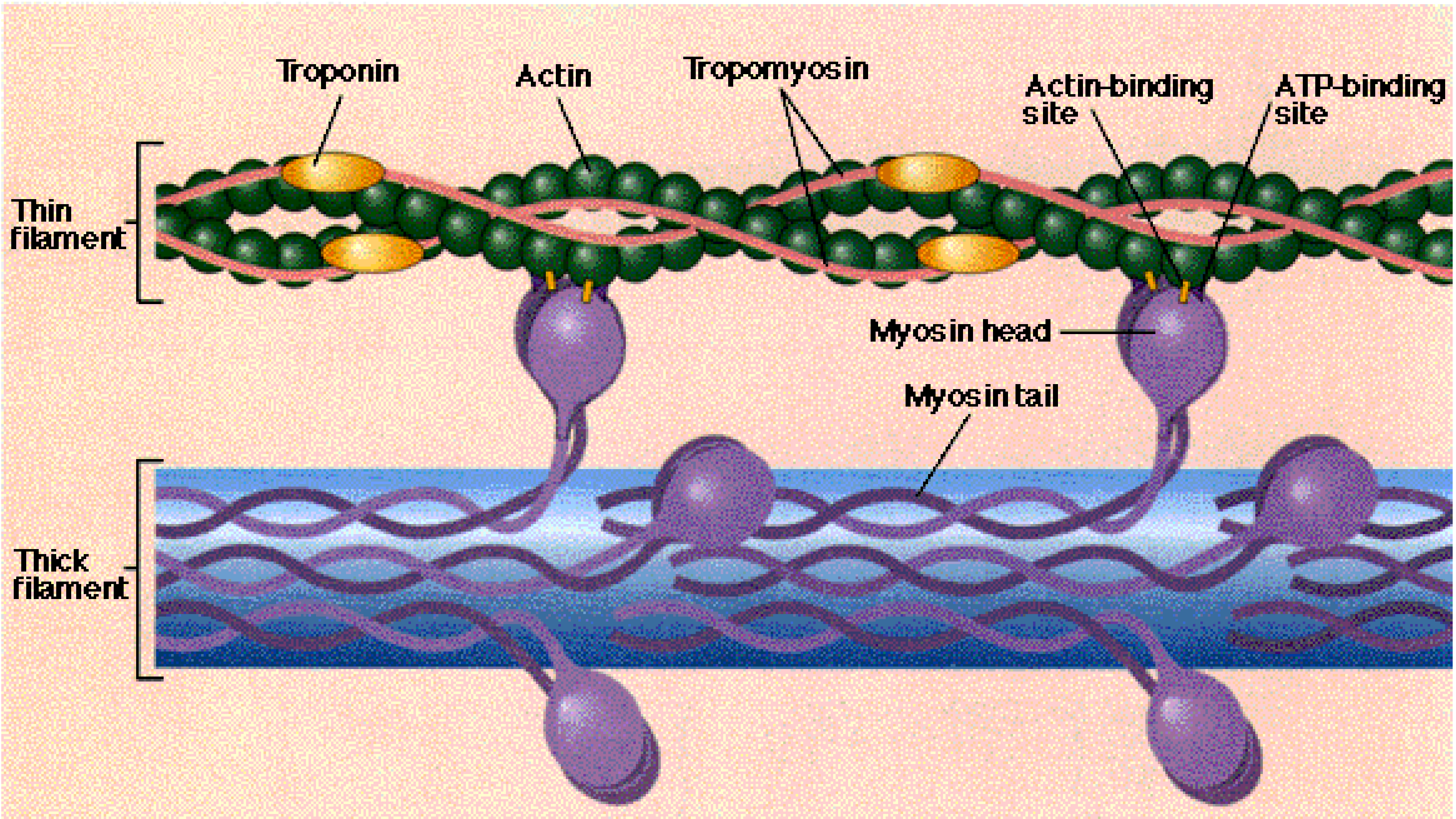


THICK FILAMENT



Central
bare zone
43 nm
120°
14.3 nm

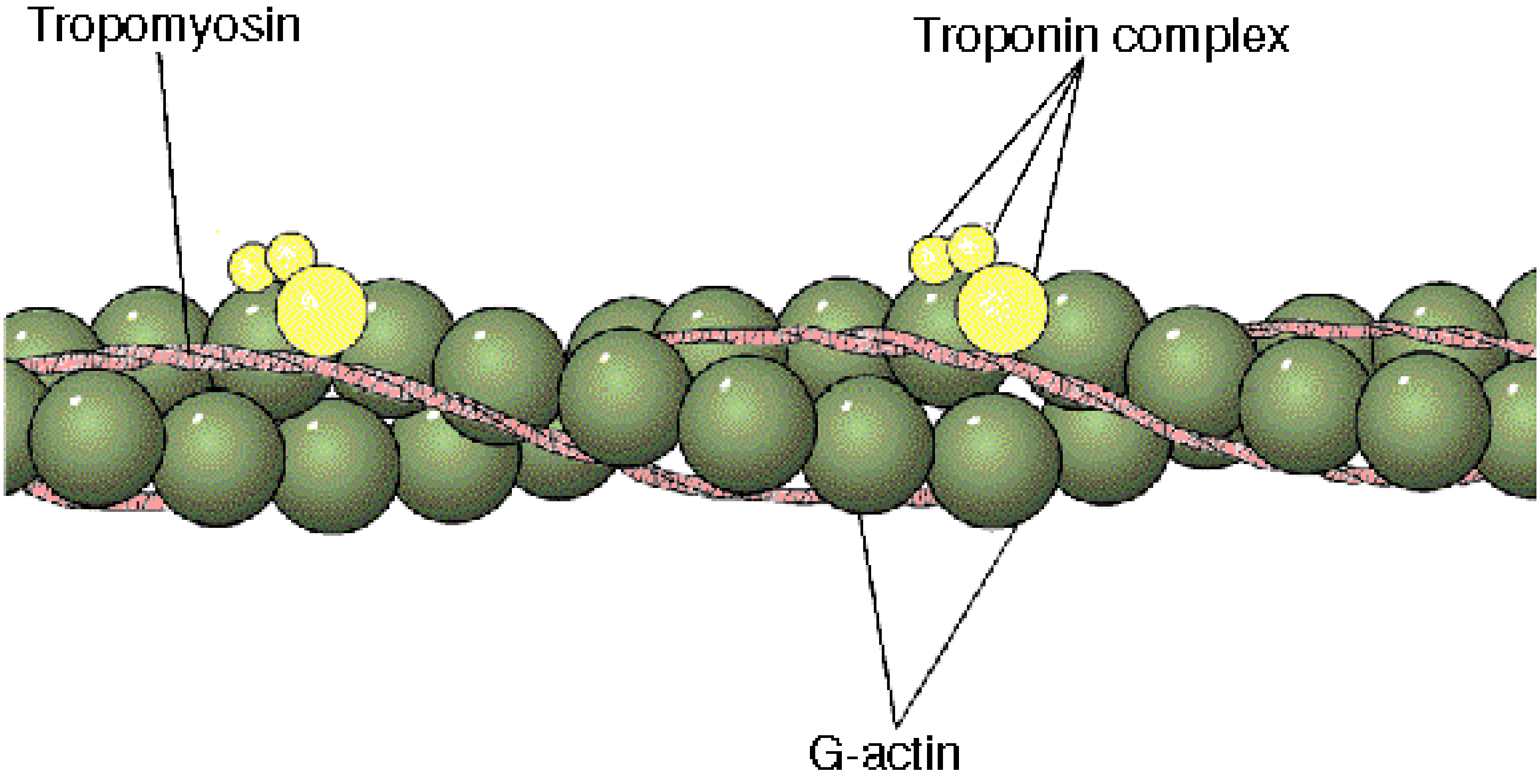
Structure of Myosin. Figure 12.12

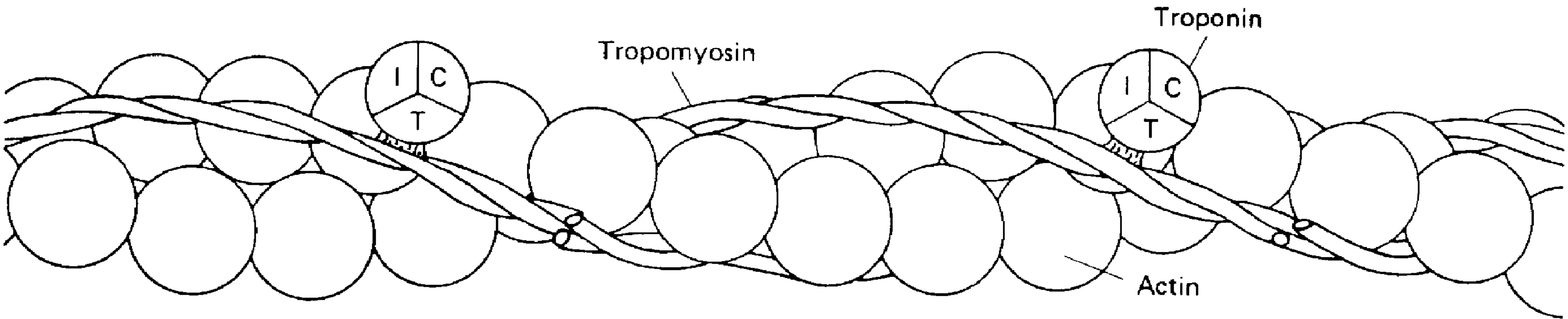


THIN FILAMENTS

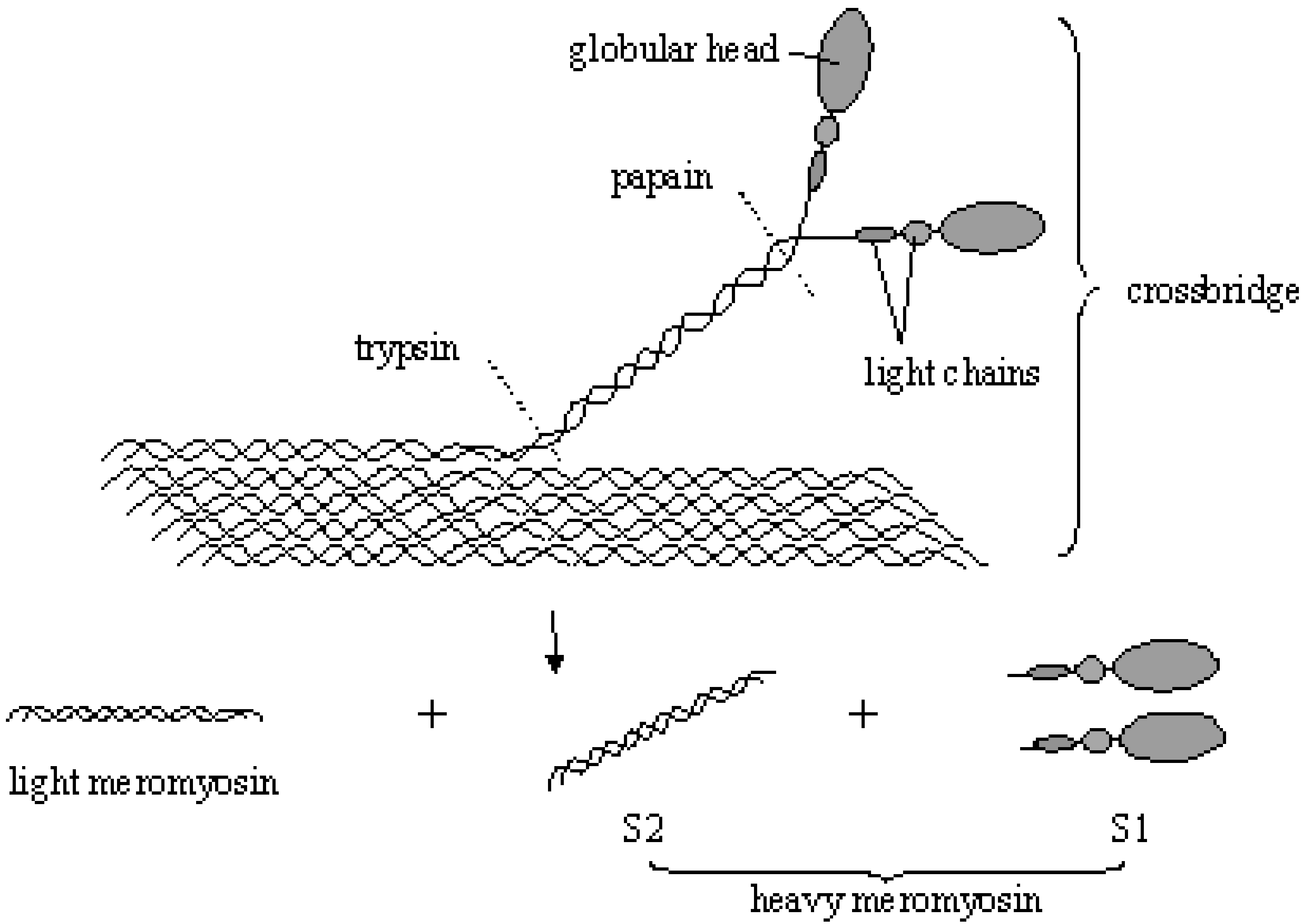
- Actin
- Tropomyosin
- Troponin

Troponin and Tropomyosin. Figure 12.14

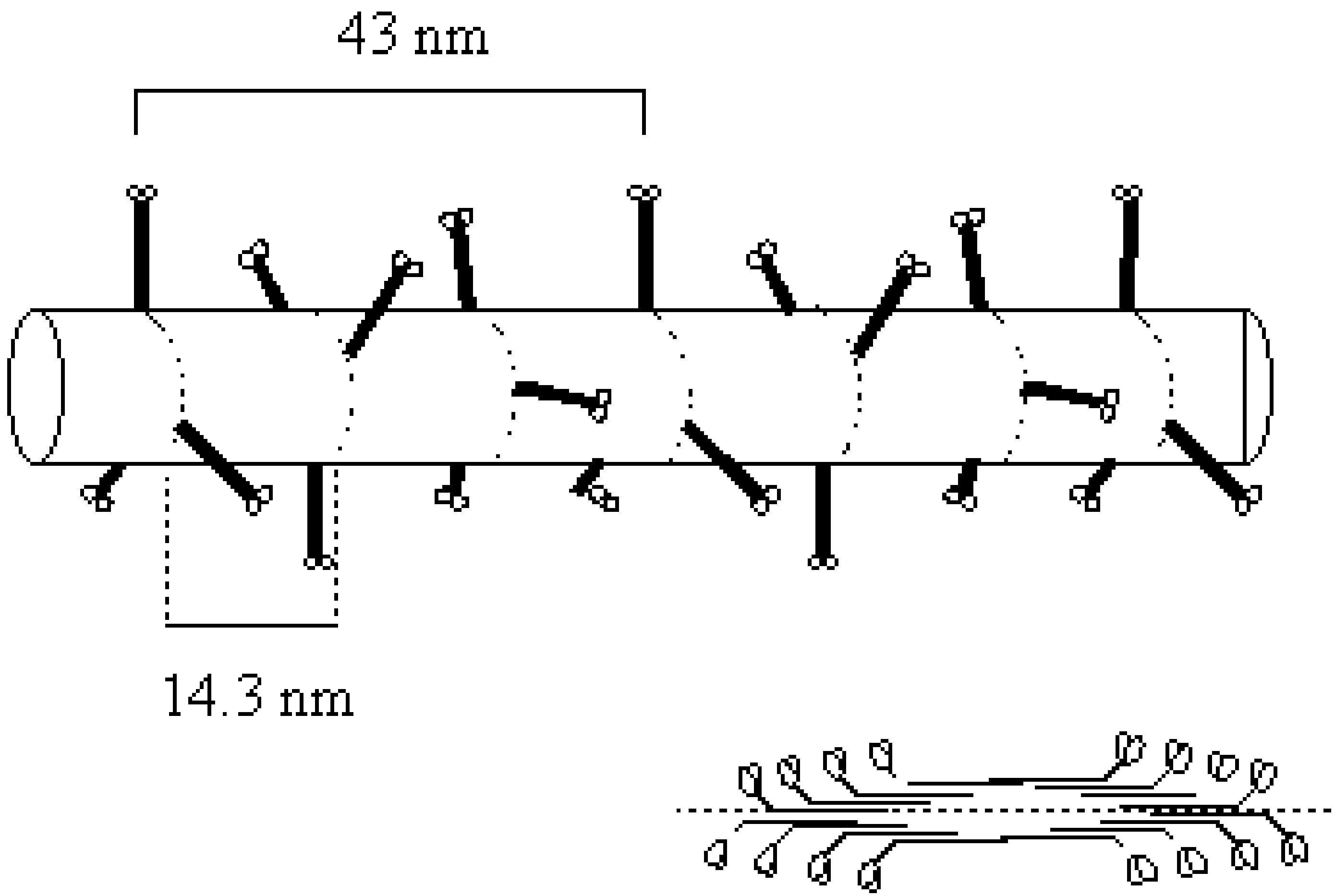



Troponin
Tropomyosin
I
C
T
I
C
T
Actin

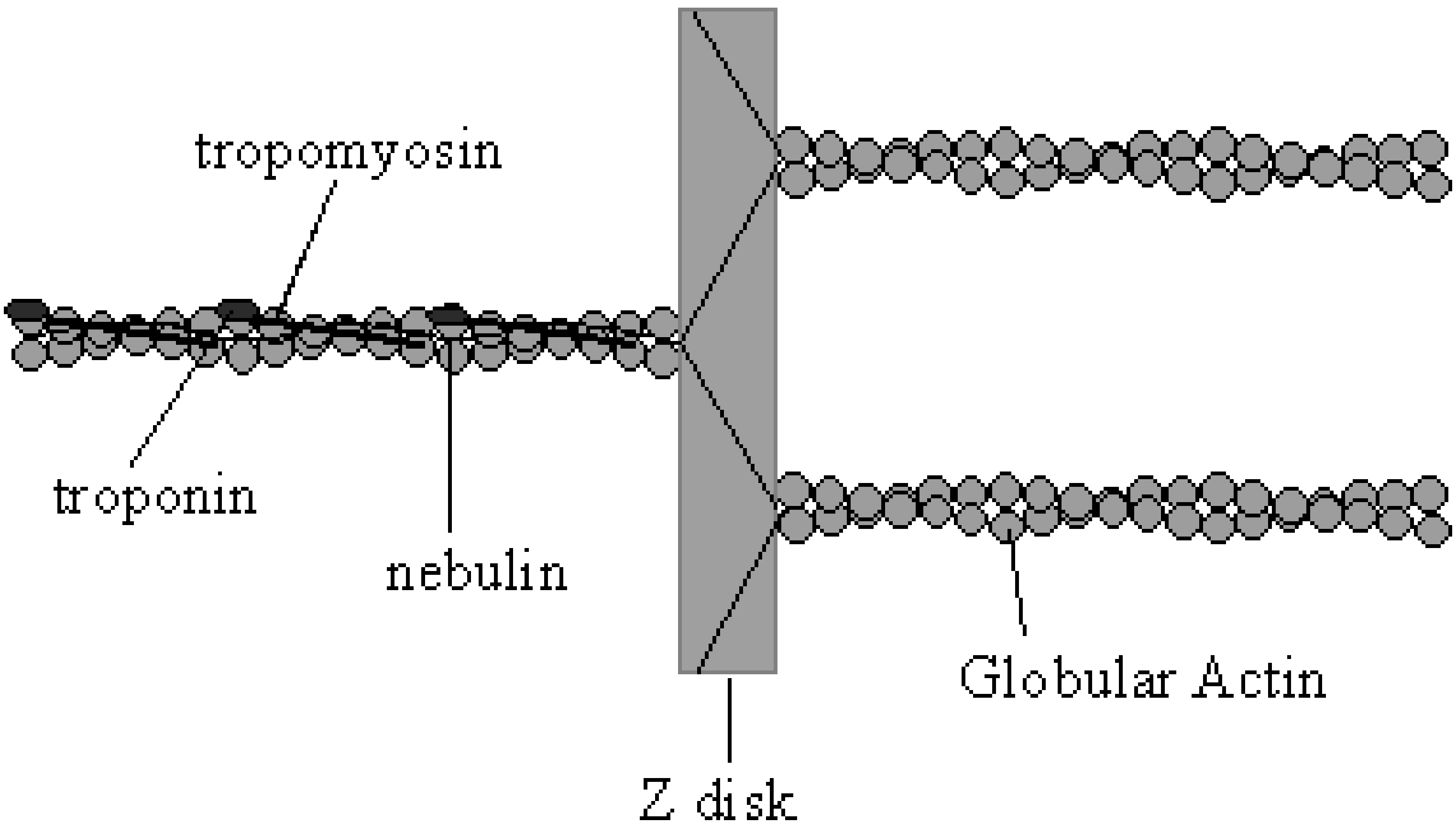
Structure of Myosin

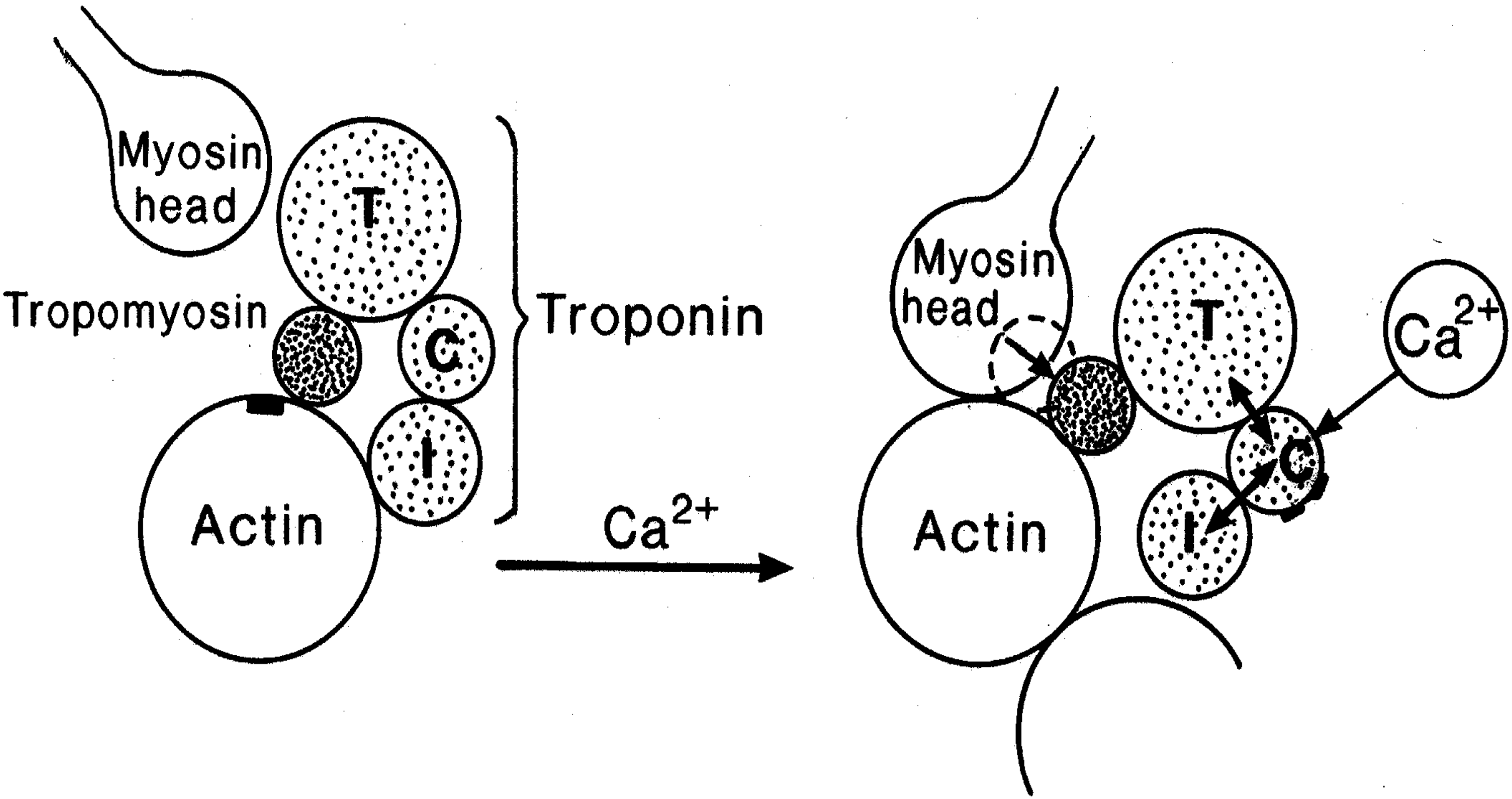


Structure of thick filament



Thin Filaments



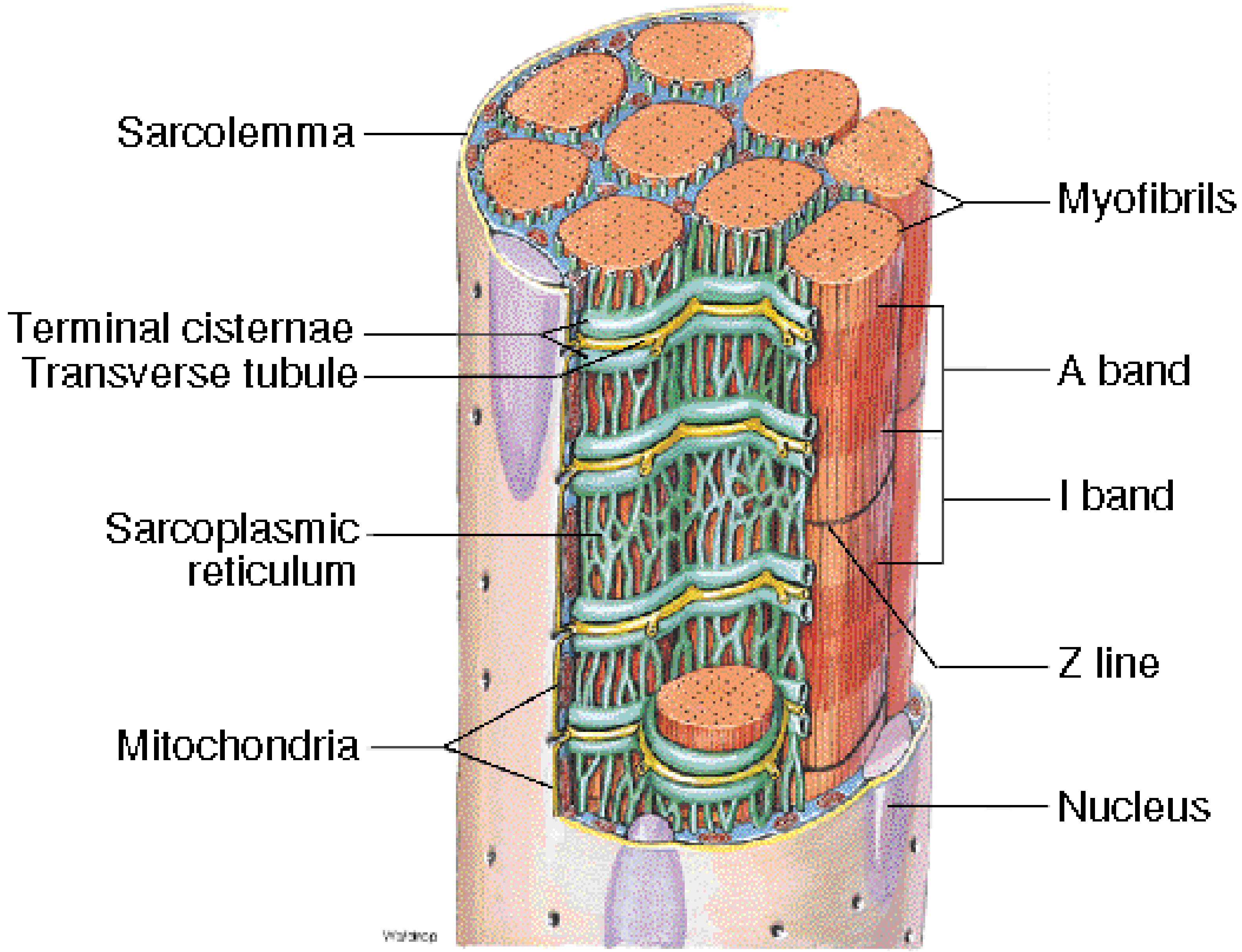


Myosin head
Tropomyosin
T
C
I
Troponin
Actin
Ca^{2+}
Myosin head
T
Ca^{2+}
C
I
Actin

THE MUSCLE CELL

SARCOPLASMIC RETICULUM

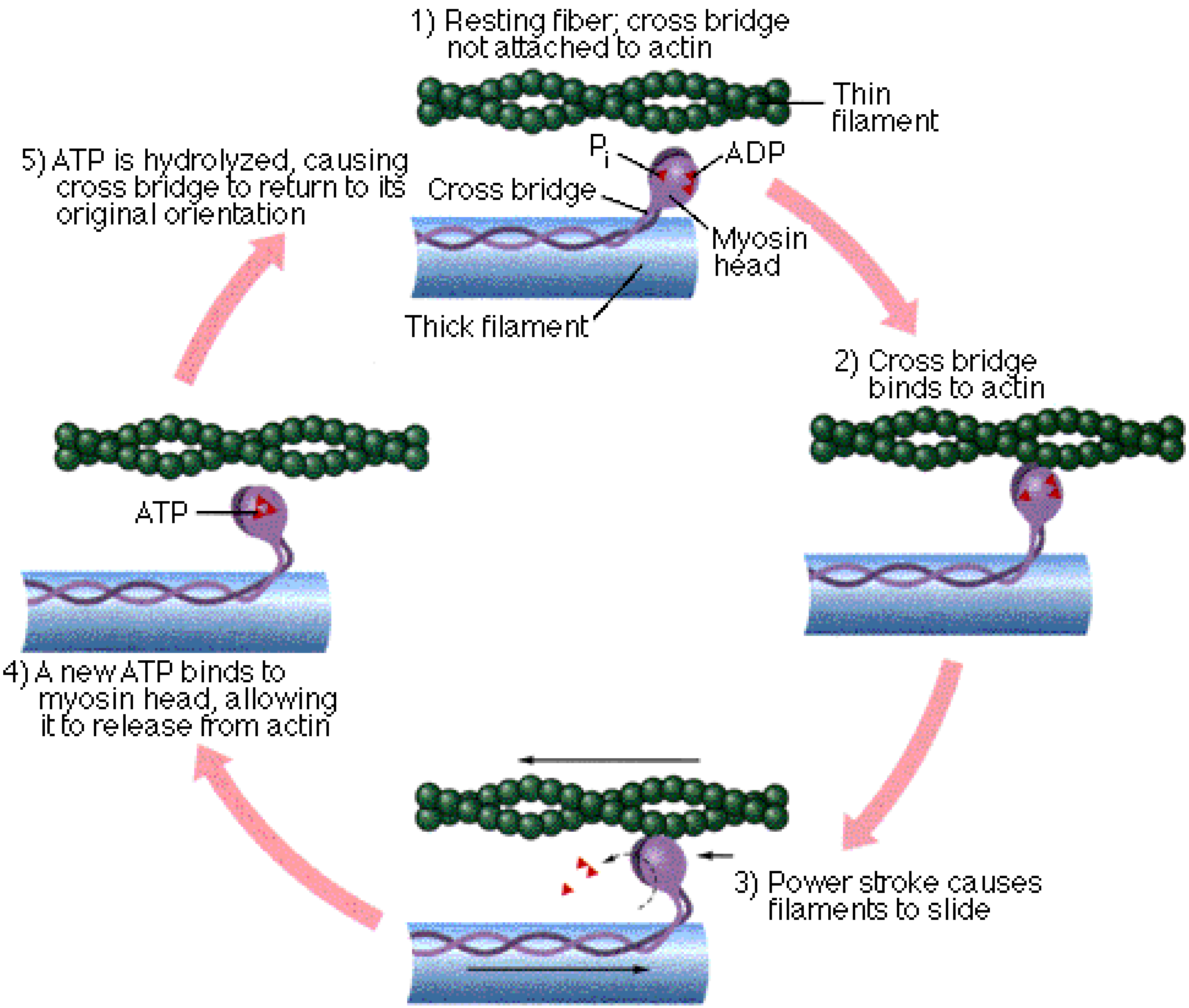
Sarcoplasmic Reticulum. Figure 12.16



MECHANISM
OF
CONTRACTION

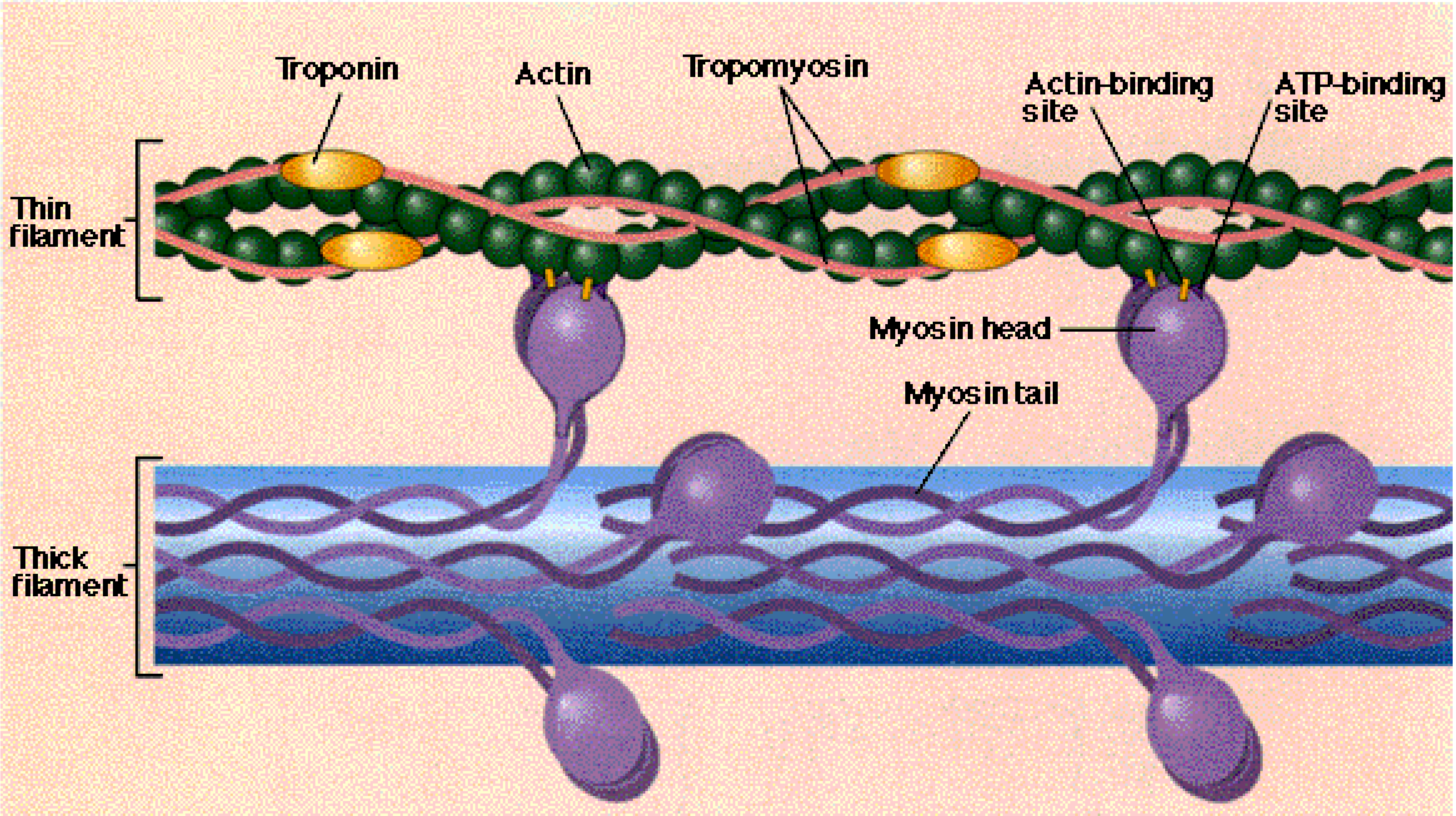
From Stuart Ira Fox, HUMAN PHYSIOLOGY, 5th ed. (c) 1995 Times Mirror Higher Education Group, Inc. Dubuque, Iowa.

Cross-Bridge Cycle. Figure 12.13

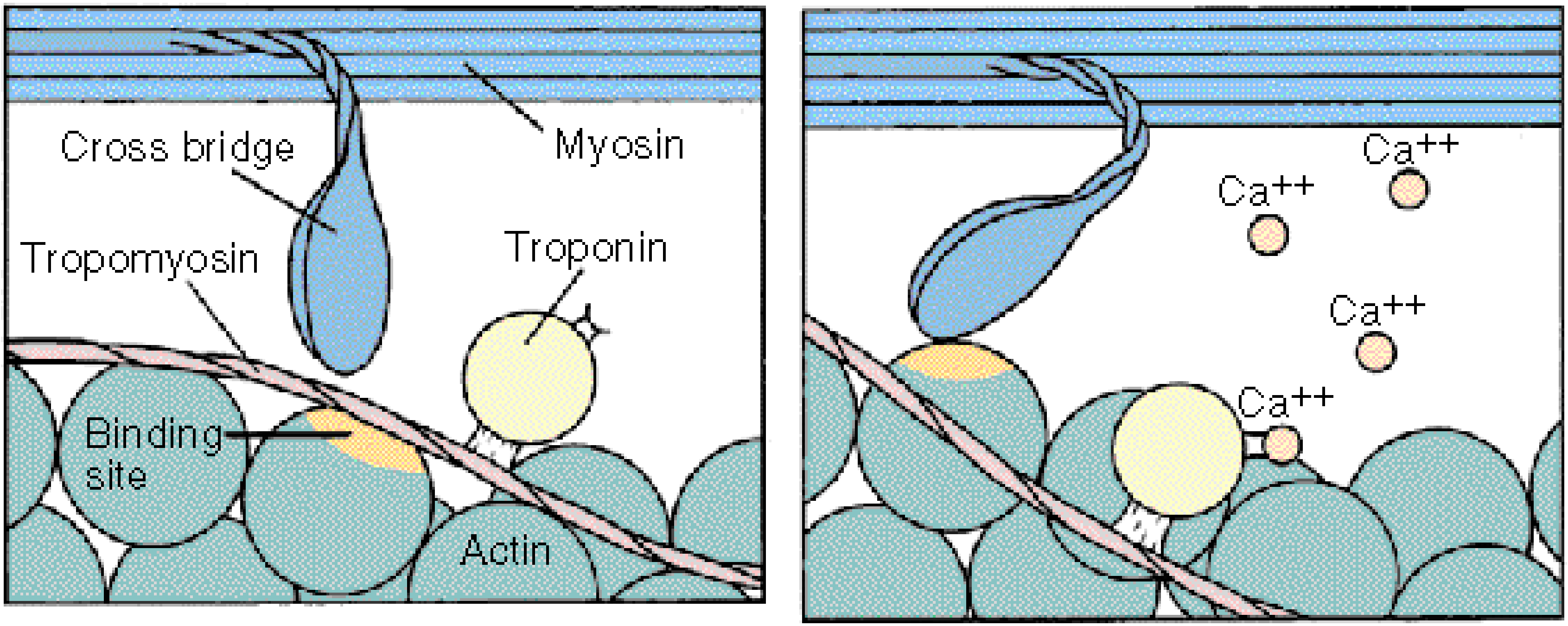


From Stuart Ira Fox, HUMAN PHYSIOLOGY, 5th ed. (c) 1995 Times Mirror Higher Education Group, Inc. Dubuque, Iowa.

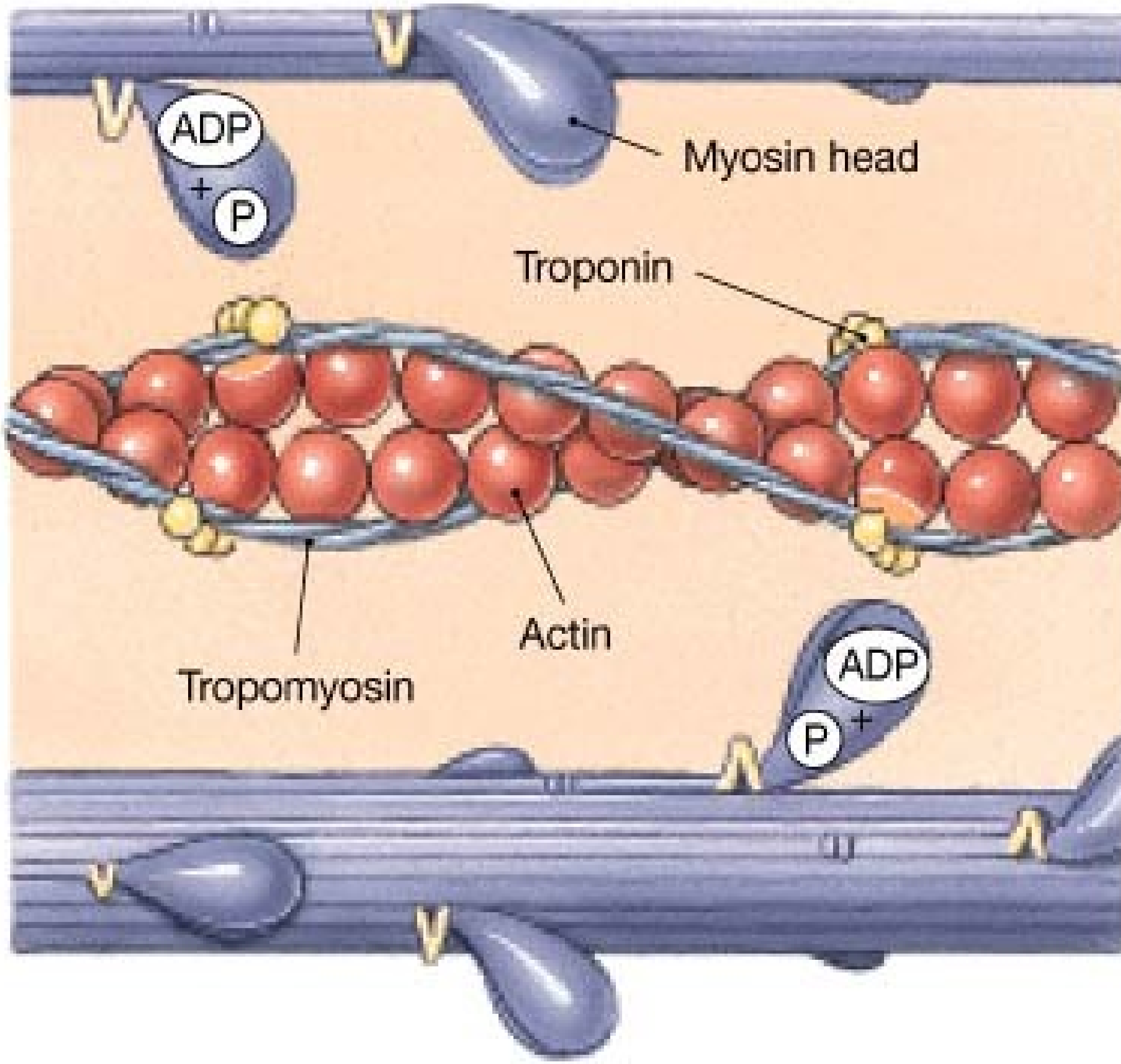
Structure of Myosin. Figure 12.12



Myosin Cross Bridges. Figure 12.15

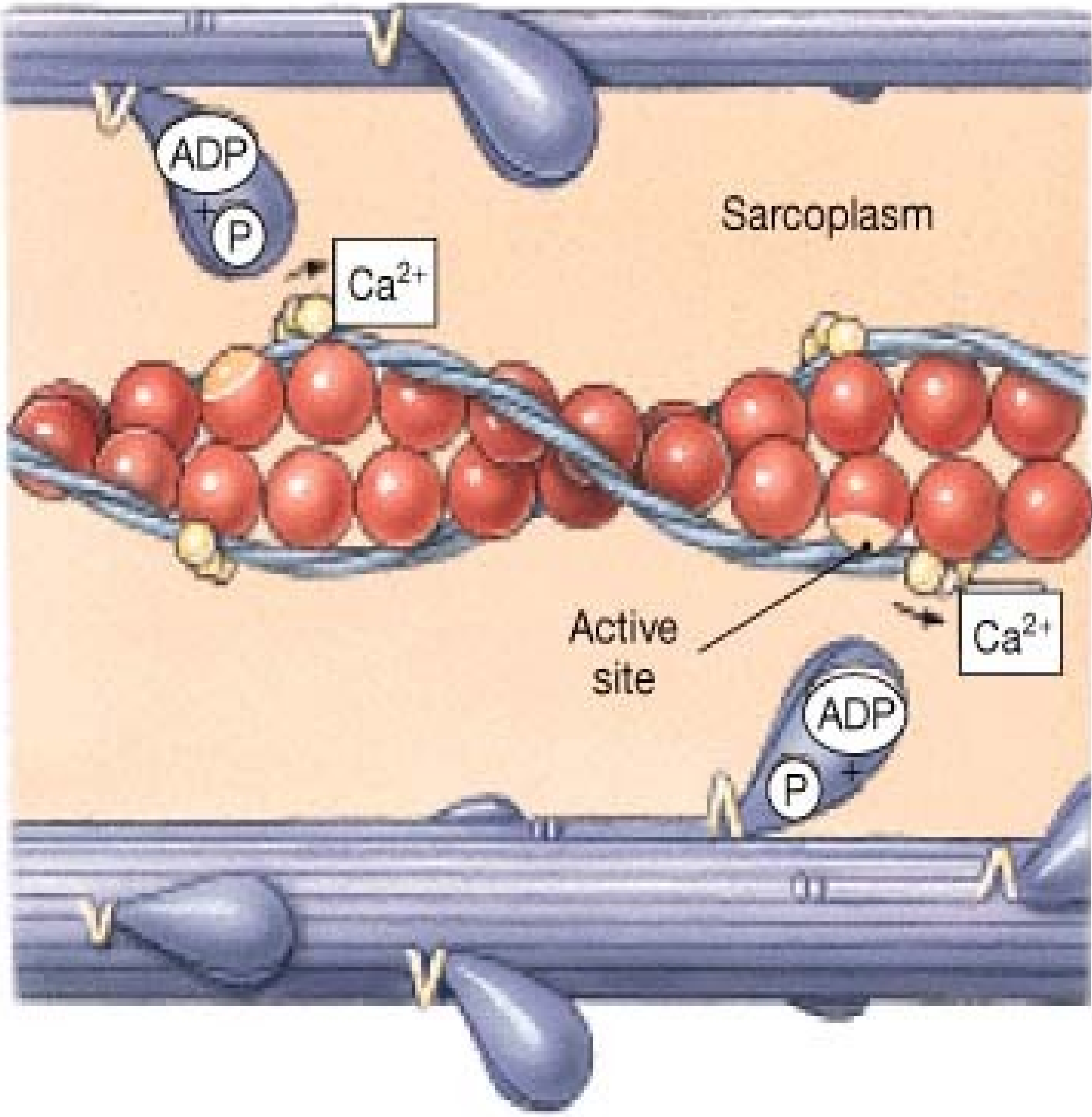


• *FIGURE 10-8*
Molecular Events of the Contraction Process



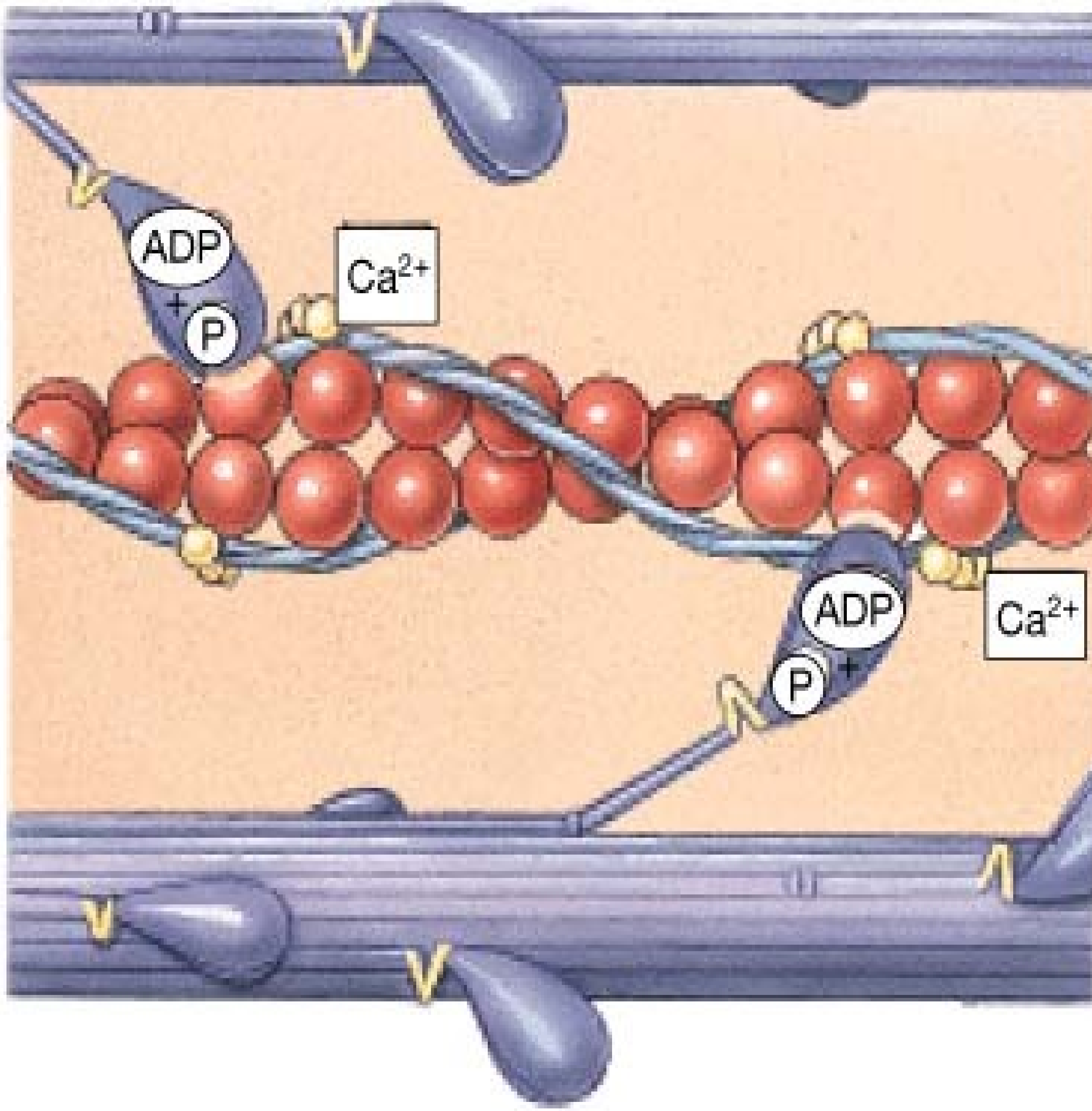
Resting sarcomere

FIGURE 10-8
Molecular Events of the Contraction Process



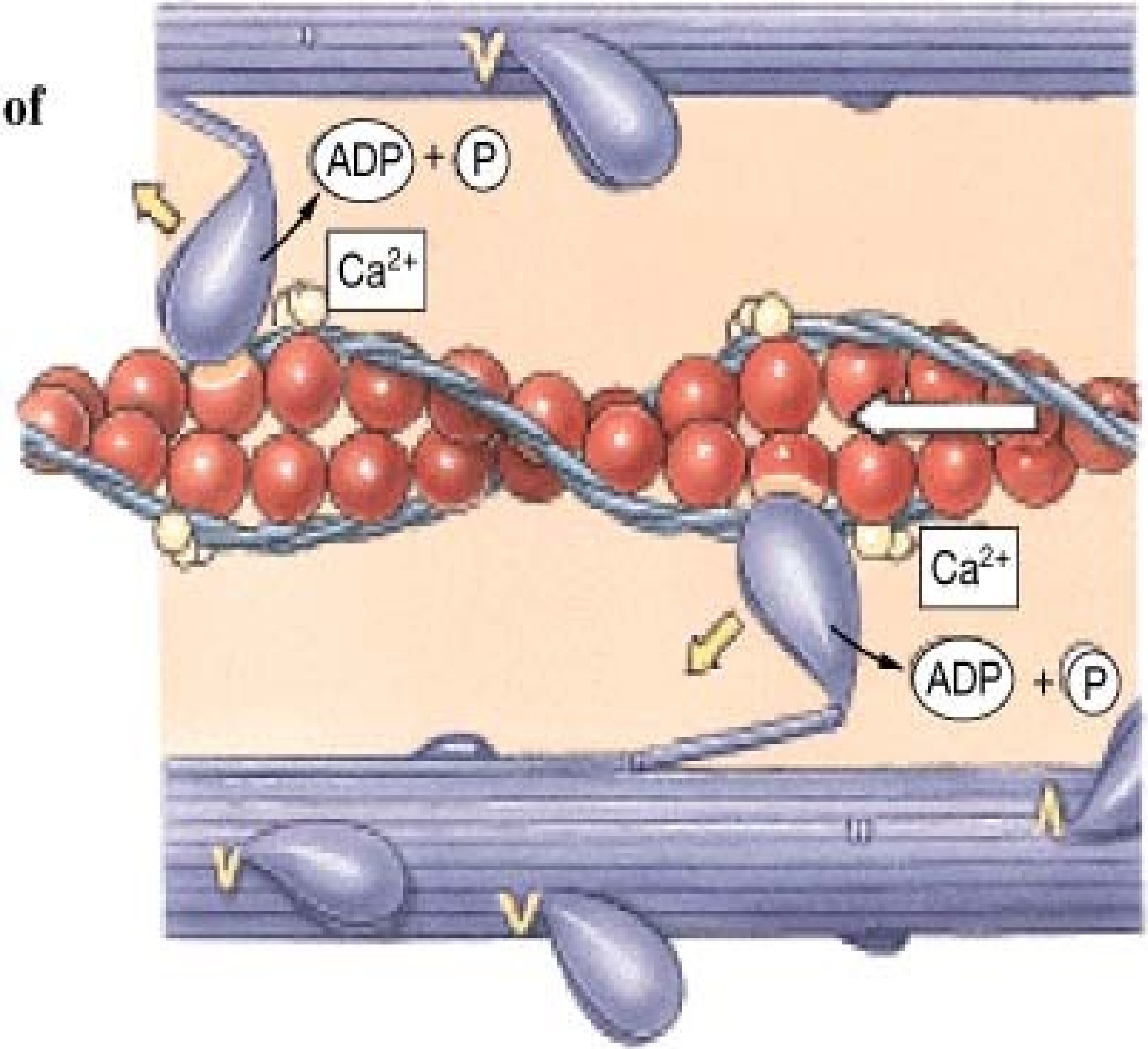
Step 1: Active-site exposure

FIGURE 10-8
Molecular Events of the Contraction Process



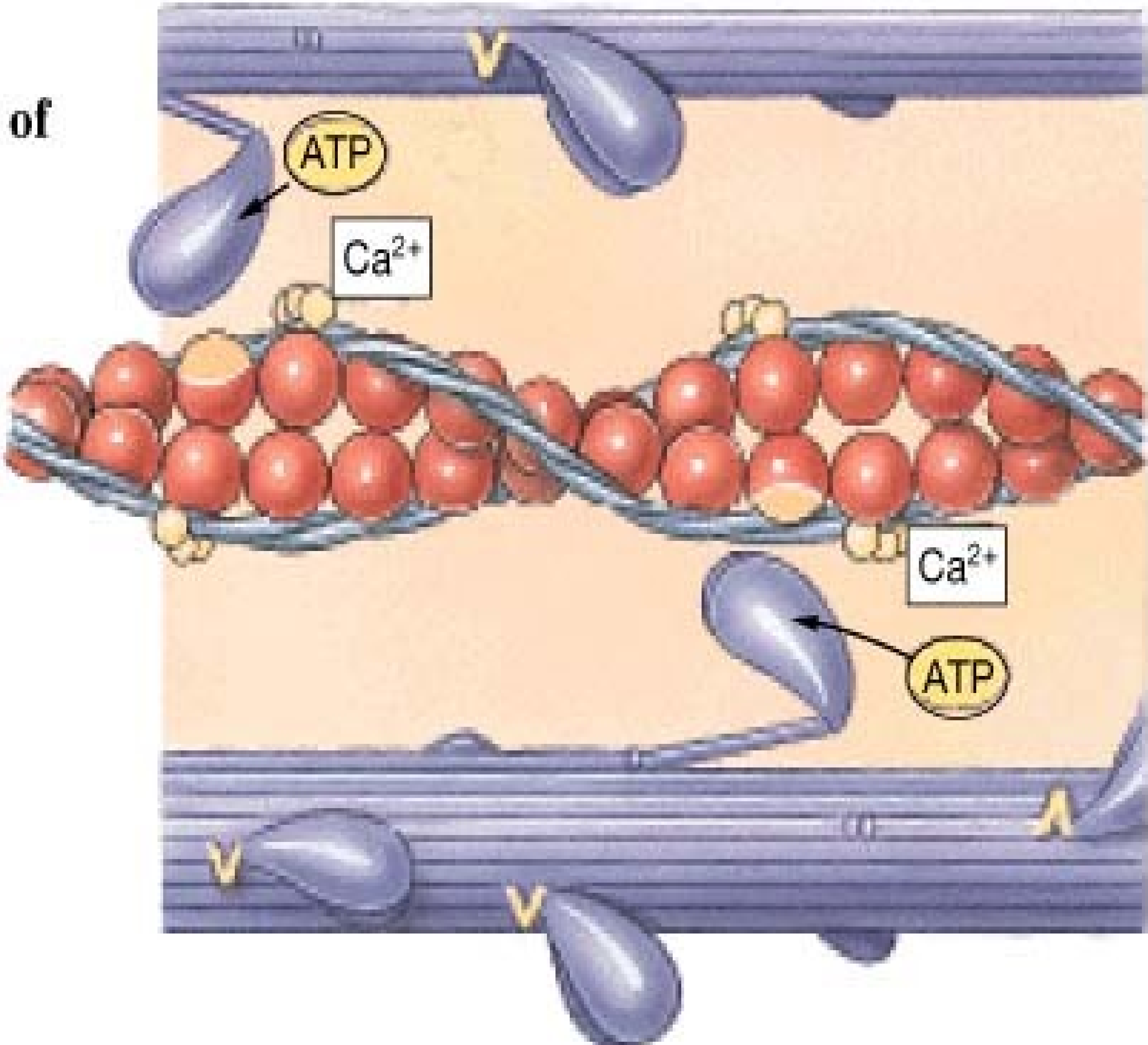
Step 2: Cross-bridge attachment

FIGURE 10-8
Molecular Events of the Contraction Process



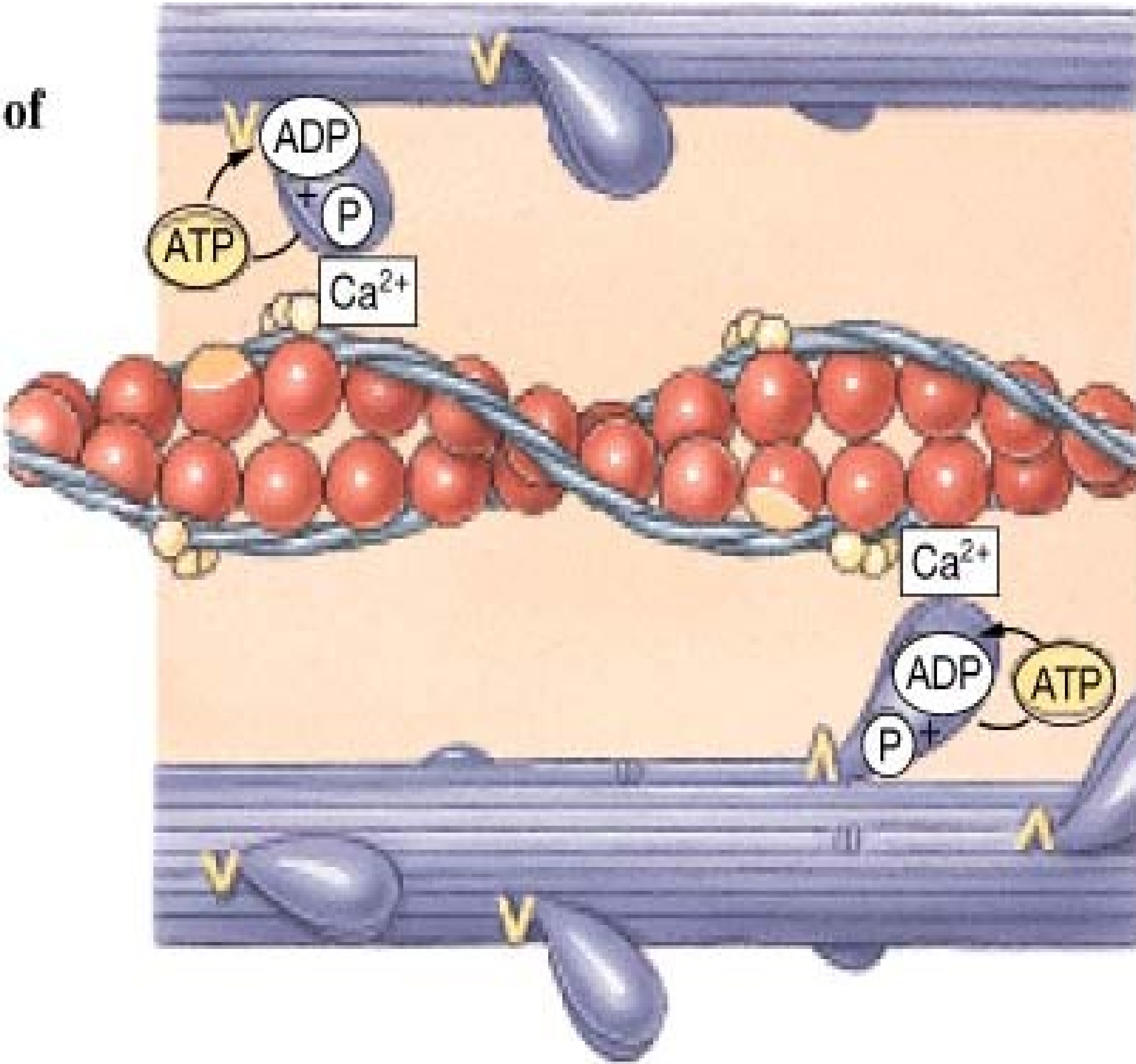
Step 3: Pivoting of myosin head

FIGURE 10-8 Molecular Events of the Contraction Process

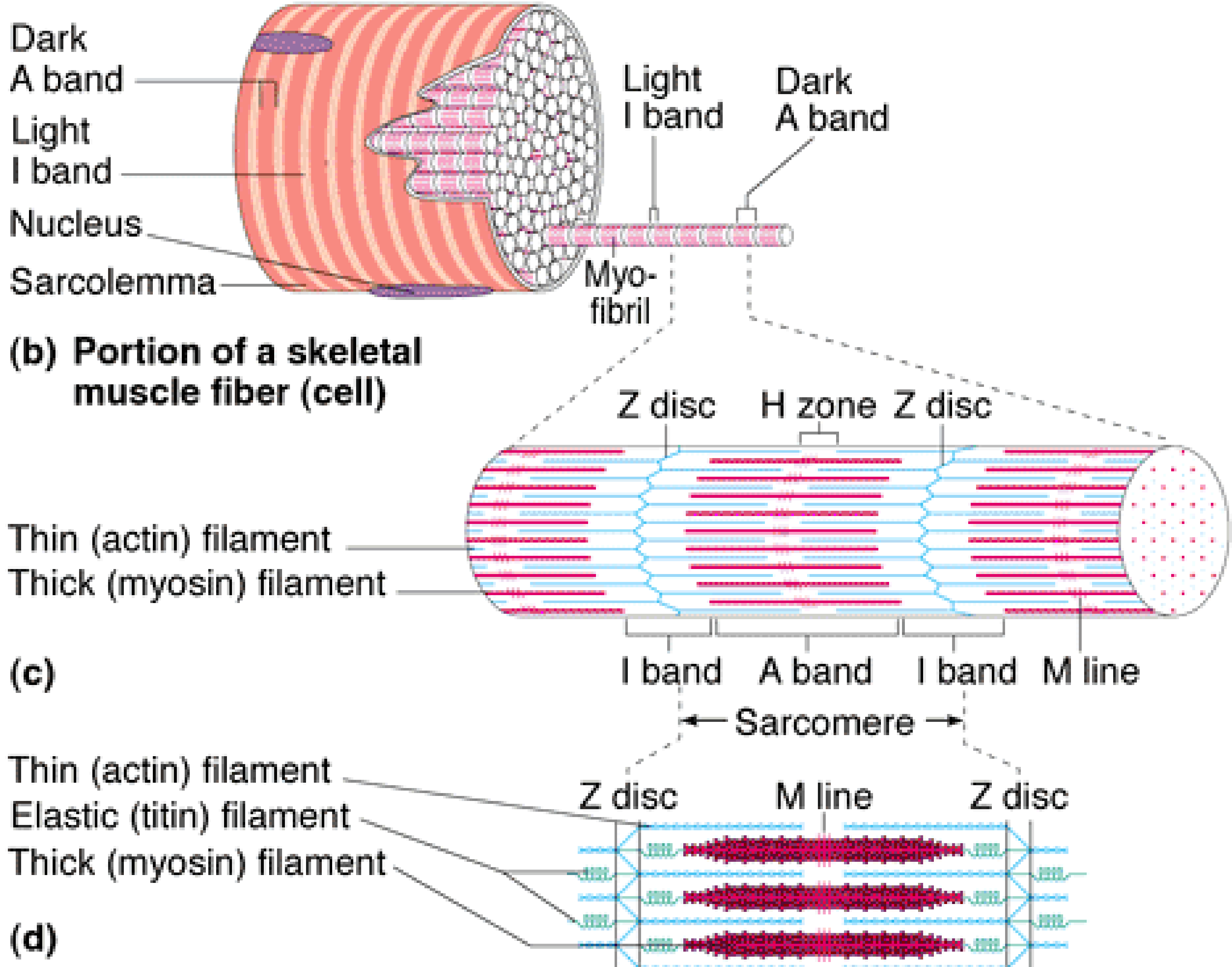


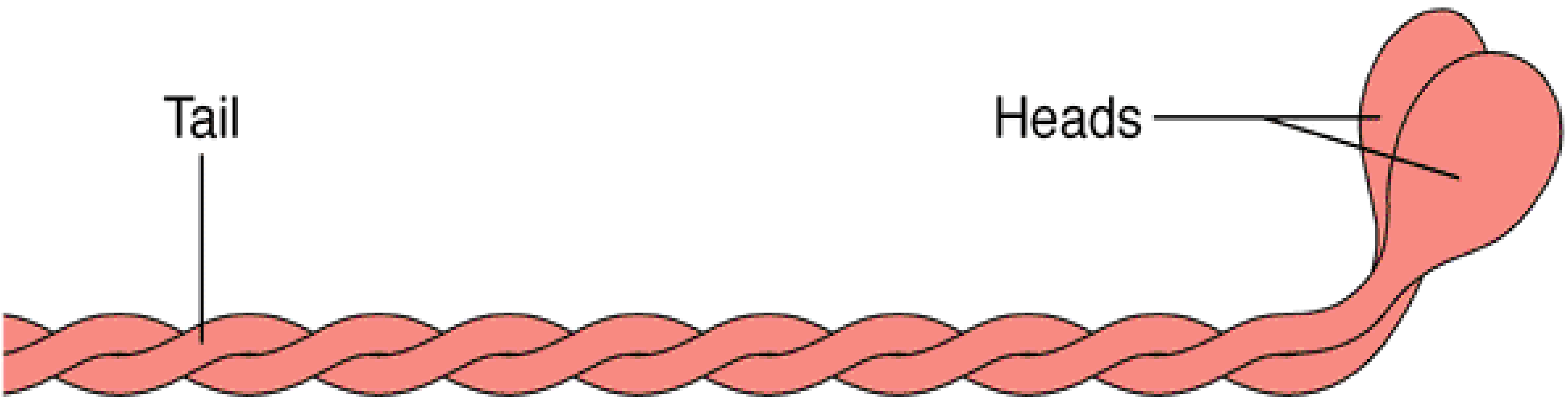
Step 4: Cross-bridge detachment

FIGURE 10-8
Molecular Events of the Contraction Process

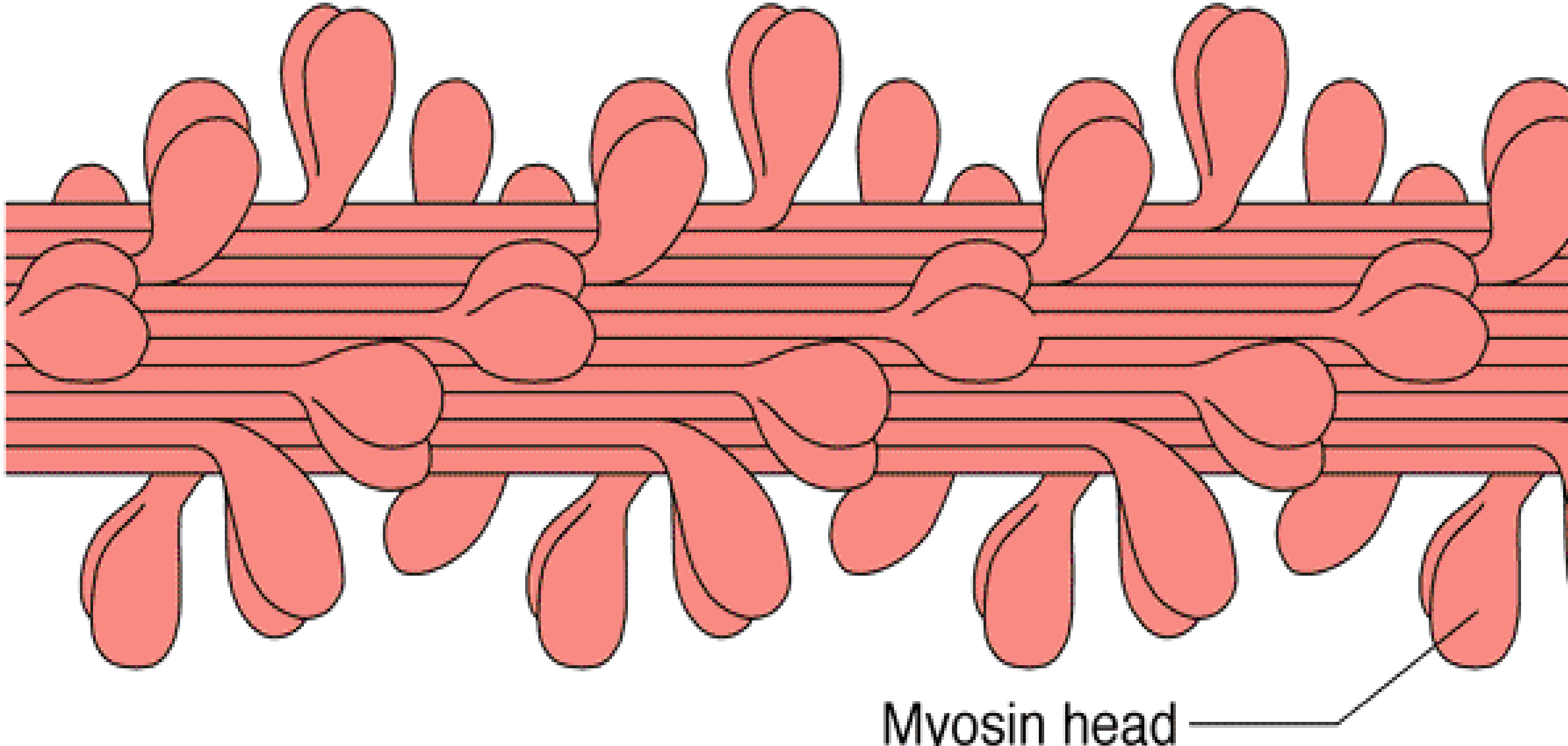


Step 5: Myosin reactivation

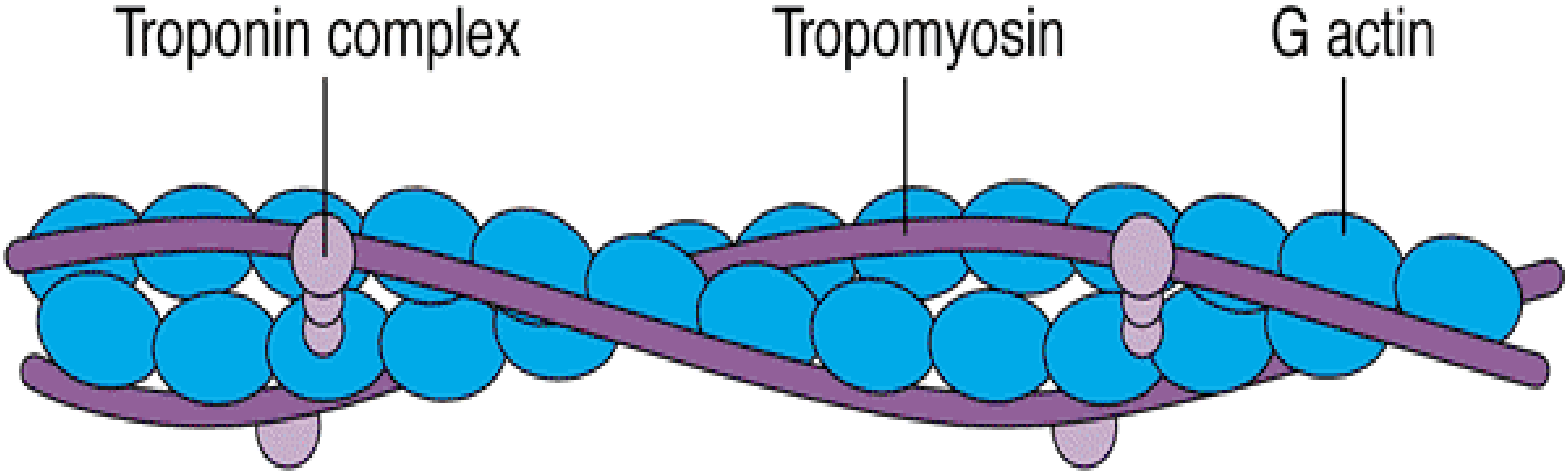

Dark
A band
Light
I band
Nucleus
Sarcolemma
Light
I band
Dark
A band
Myo-
fibril
(b) Portion of a skeletal
muscle fiber (cell)
Z disc
H zone
Z disc
Thin (actin) filament
Thick (myosin) filament
I band
A band
I band
M line
(c)
Sarcomere
Thin (actin) filament
Elastic (titin) filament
Thick (myosin) filament
Z disc
M line
Z disc
(d)



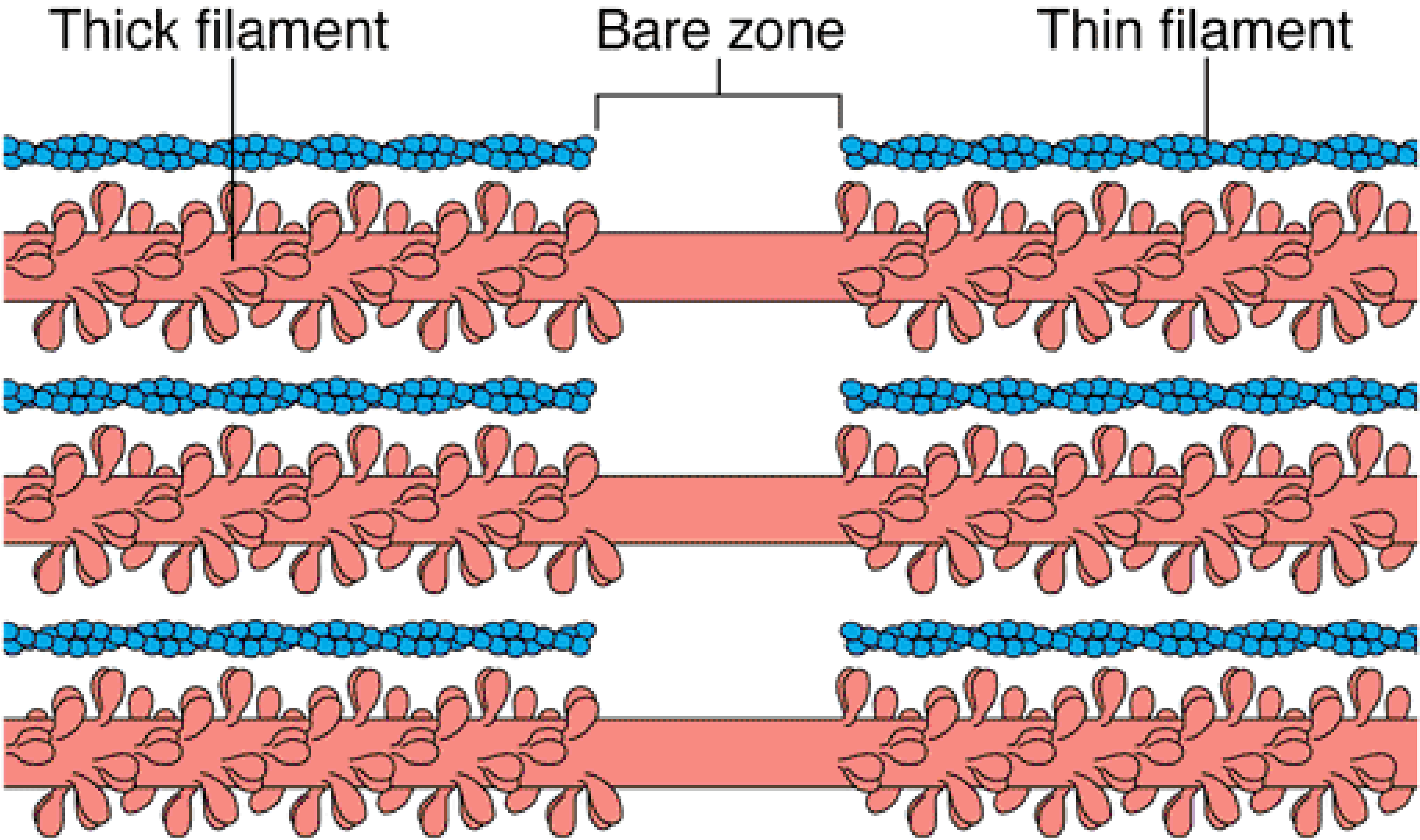
(a) Myosin molecule



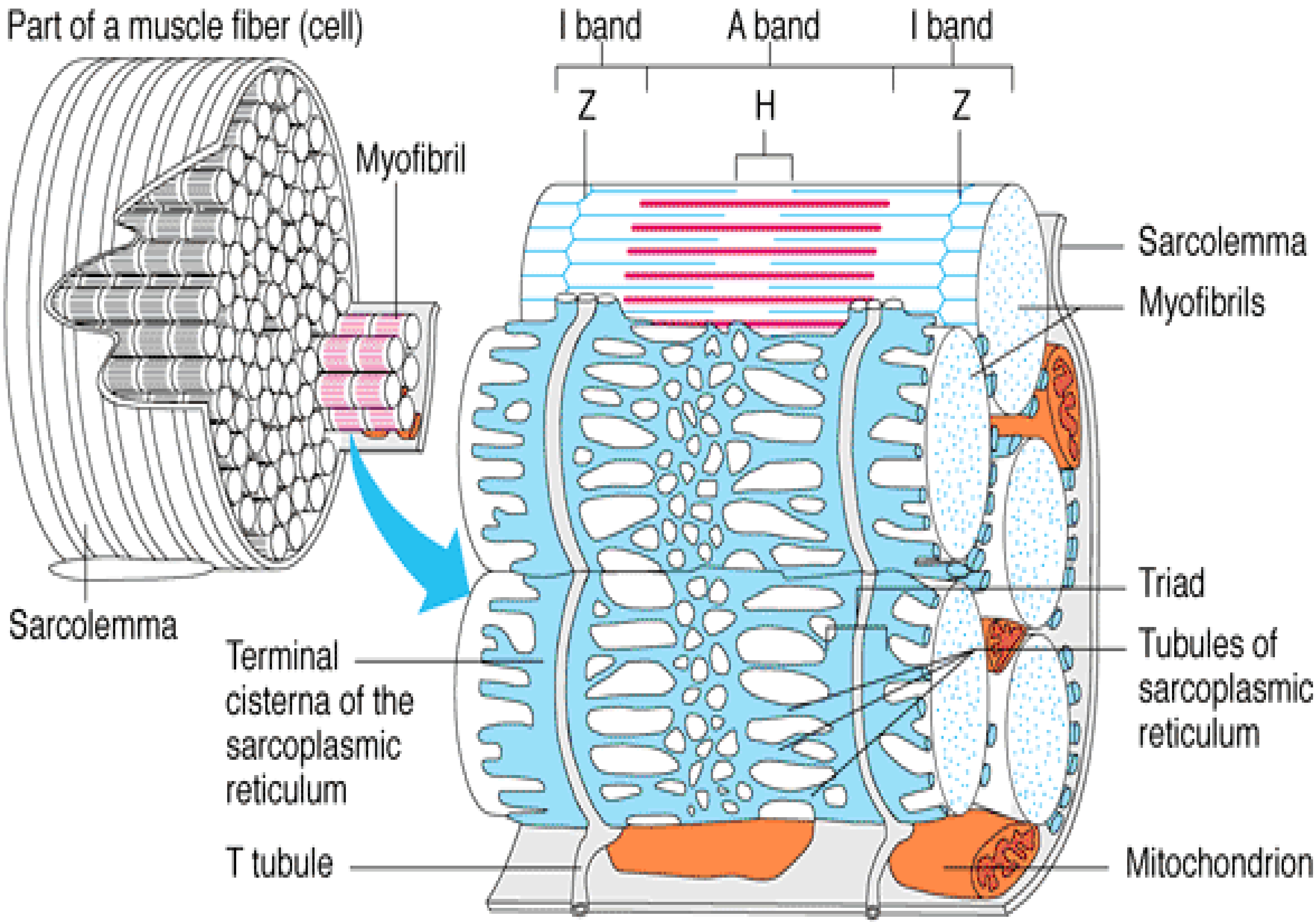
(b) Portion of a thick filament

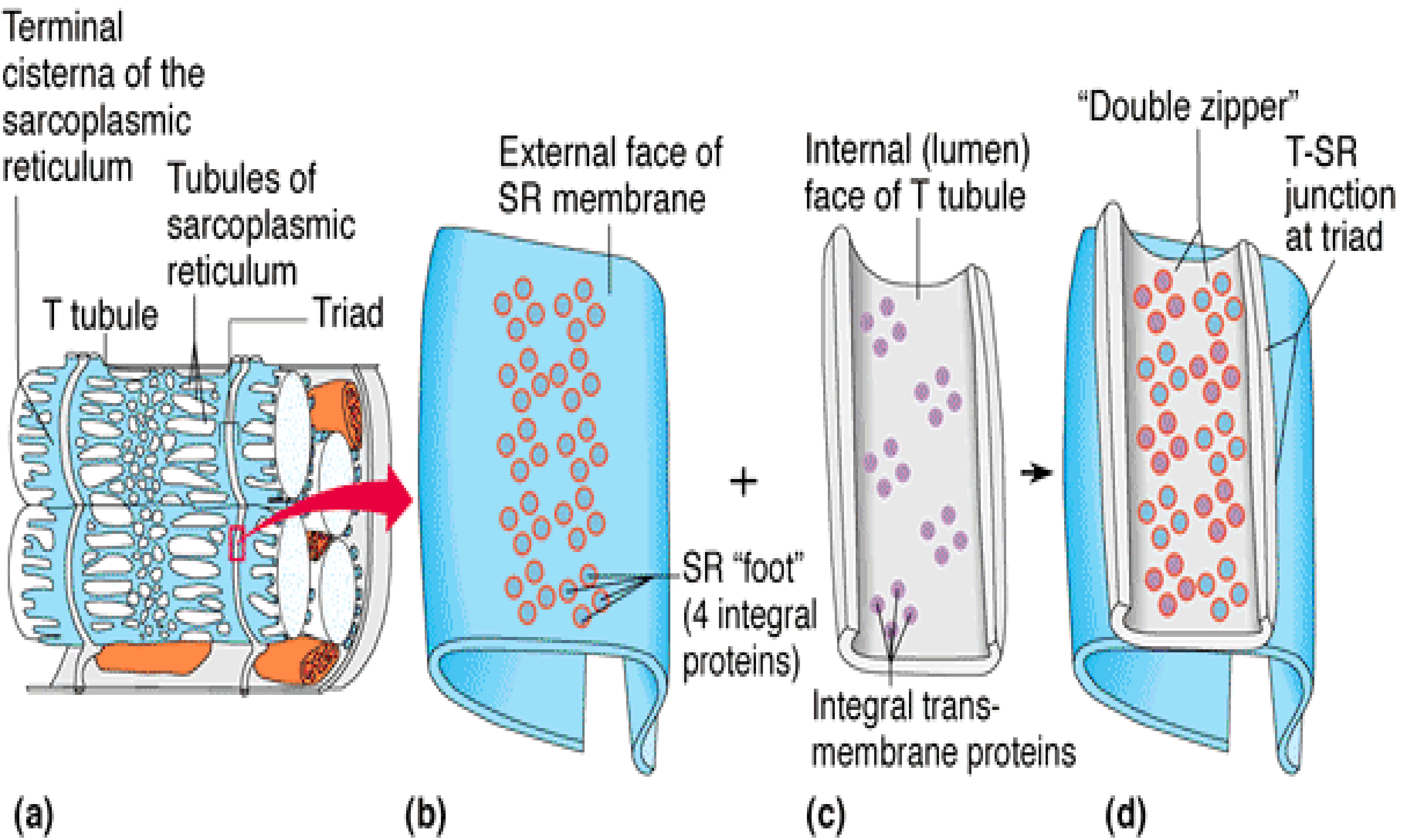


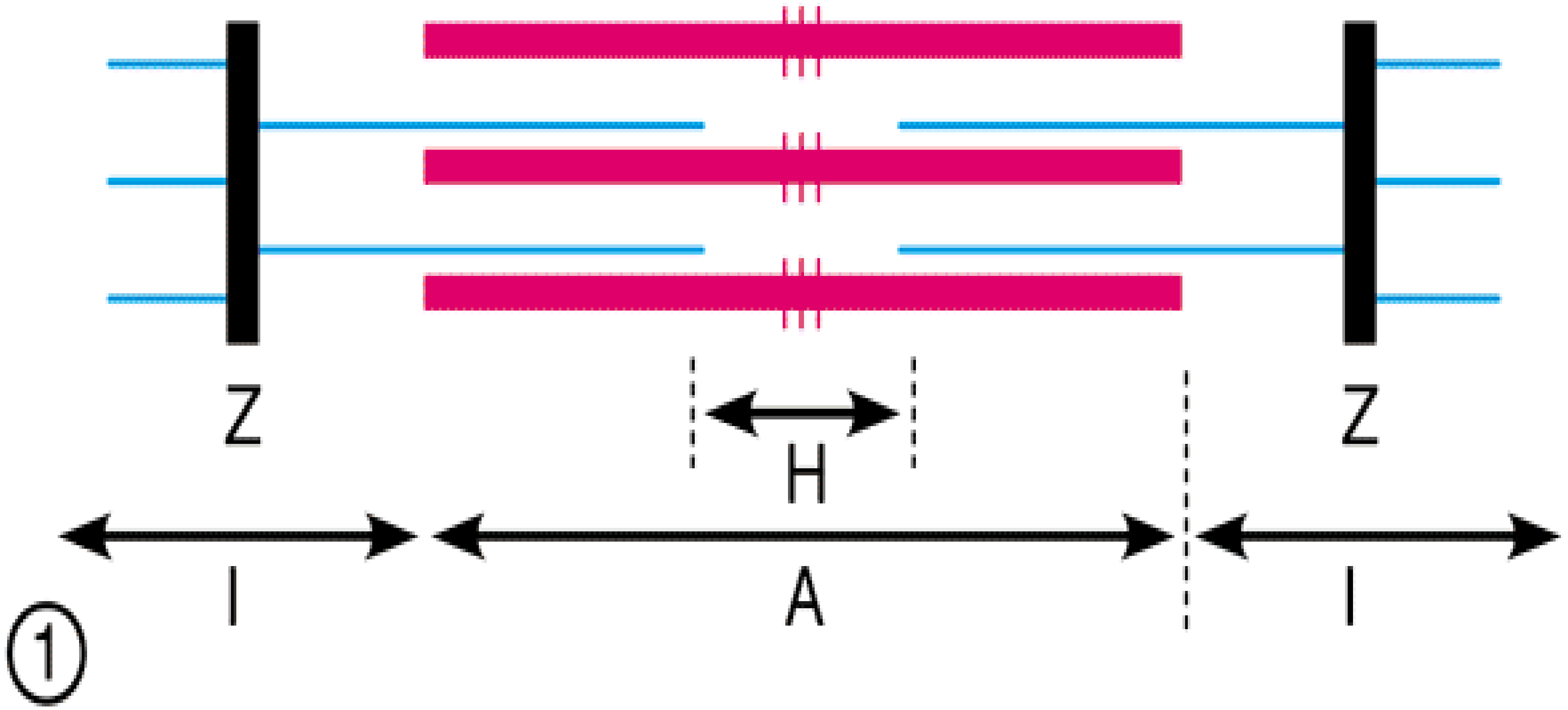
(c) Portion of a thin filament

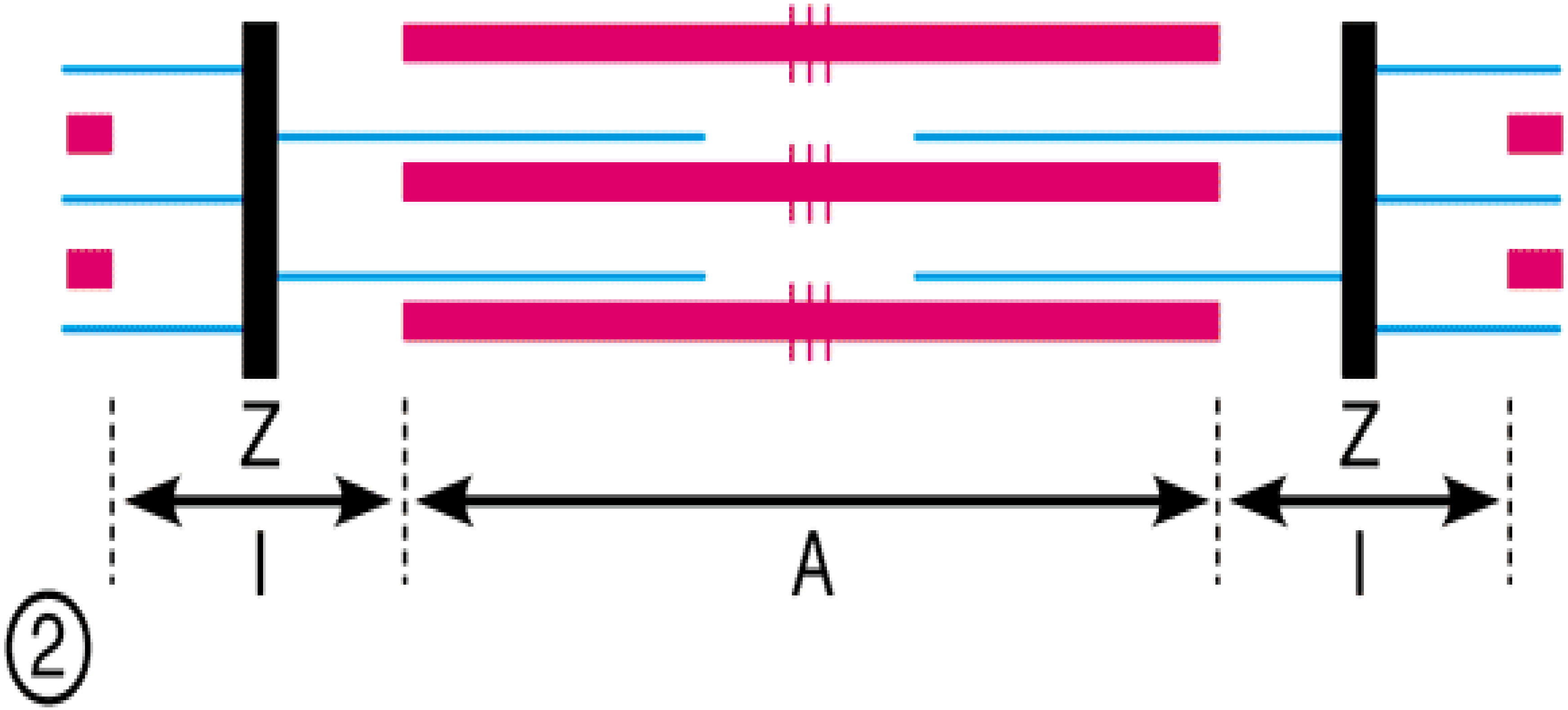


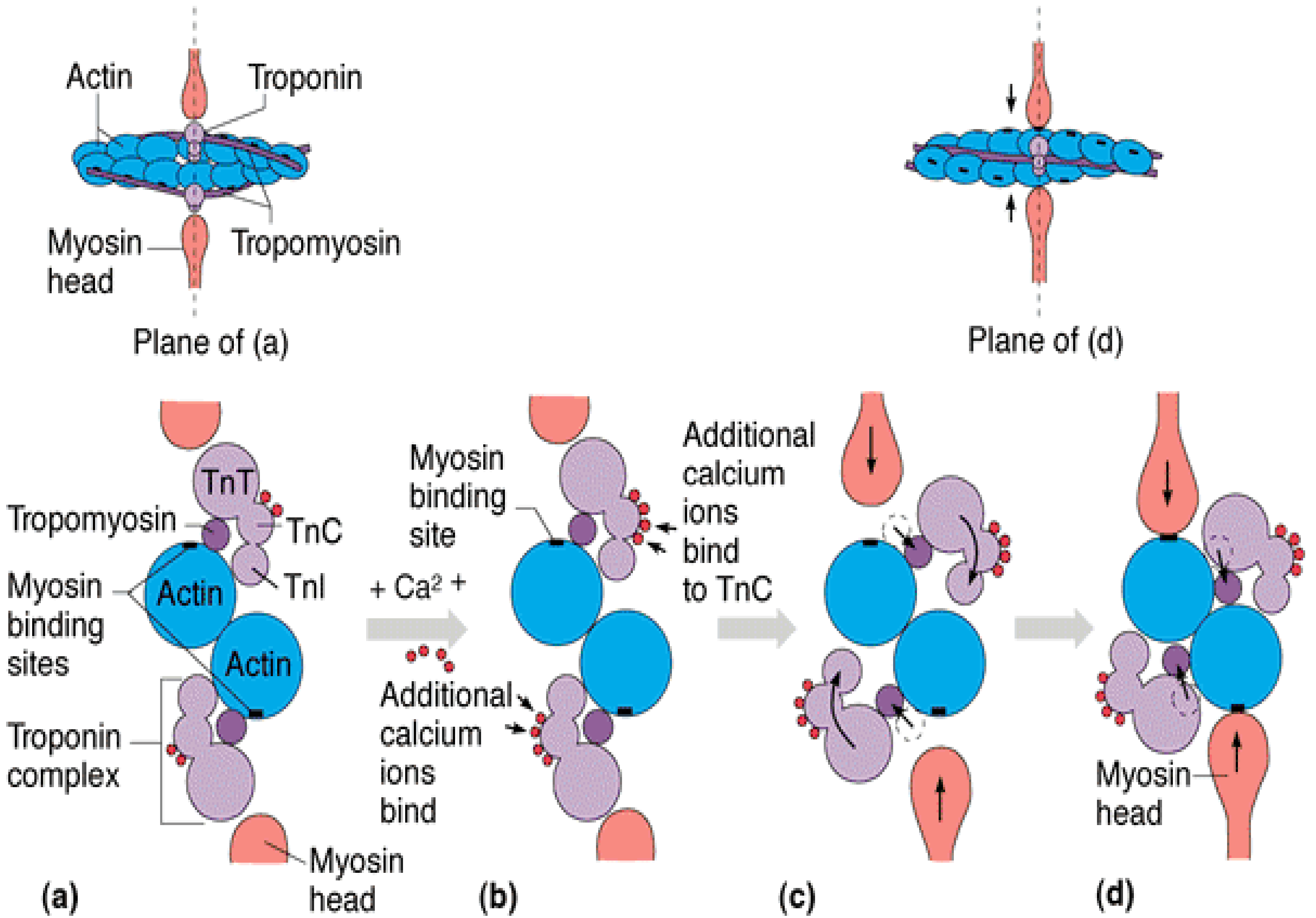
(d) Longitudinal section of filaments within one sarcomere of a myofibril


Part of a muscle fiber (cell)
Myofibril
Sarcolemma
I band
A band
I band
Z
H
Z
Sarcolemma
Myofibrils
Triad
Tubules of sarcoplasmic reticulum
Terminal cisterna of the sarcoplasmic reticulum
T tubule
Mitochondrion


Terminal cisterna of the sarcoplasmic reticulum
Tubules of sarcoplasmic reticulum
T tubule
Triad
External face of SR membrane
SR "foot" (4 integral proteins)
+
Internal (lumen) face of T tubule
Integral trans-membrane proteins
"Double zipper"
T-SR junction at triad
(a)
(b)
(c)
(d)


Z
Z
H
I
A
I
1


Z
Z
I
A
I
2


Actin
Troponin
Myosin
head
Tropomyosin
Plane of (a)
Plane of (d)
TnT
Tropomyosin
TnC
Myosin
binding
sites
Actin
TnI
Actin
Troponin
complex
Myosin
head
(a)
+ Ca2 +
Additional
calcium
ions
bind
Myosin
binding
site
(b)
Additional
calcium
ions
bind
to TnC
(c)
Myosin
head
(d)

REVIEW & OBJECTIVES

- 1) Skeletal Muscle
- 2) Cardiac Muscle
- 3) Sarcomere - the functional unit
- 4) Sliding Filament Mechanism
- 5) Motor Unit
- 6) Neuromuscular Junction
- 7) Smooth Muscle

Skeletal Muscle

- *Location : attached* to bones (some attached to skin, deep fascia, or other muscles).
- *Microscopic Appearance : striated;* many nuclei in each fiber (cell); unbranched fibers.
- *Fiber Diameter: 10* to 100 micrometers.

Skeletal Muscle

- *Fiber Length : 100* micrometers to 30 centimeters (about 1 foot).
- *Nervous Control : voluntary* (conscious) control by somatic nervous system.
- *Regeneration : limited* capacity; cells cannot divide.

Skeletal Muscle

- *Functions* moves parts of the skeleton (walking, running, nodding the head, manipulating objects);
- postural muscles maintain the body in stable positions;
- the diaphragm regulates breathing by changing intrathoracic volume.

Cardiac Muscle

- *Location* : heart.
- *Microscopic Appearance : striated;* single nucleus; branched fibers with intercalated discs.
- *Fiber Diameter : 14* micrometers.
- *Fiber Length: 50* to 100 micrometers.

Cardiac Muscle

- *Nervous Control : involuntary* (unconscious) control by autonomic nervous system.
- *Hormonal Control* : epinephrine & norepinephrine increase rate and strength of contractions.
- *Regeneration* : none.
- *Function : propels* blood through the blood vessels.

CHARACTERISTICS OF MUSCLE TISSUES

- *(1)* ***Excitability*** (Irritability) : ability to generate action potentials in response to stimuli.
- *(2)* ***Contractility*** *: ability* to contract and generate a force.
- *(3)* ***Extensibility*** *: ability* to be stretched when pulled.
- *(4)* ***Elasticity*** *: ability* to return to original length after contraction or extension.

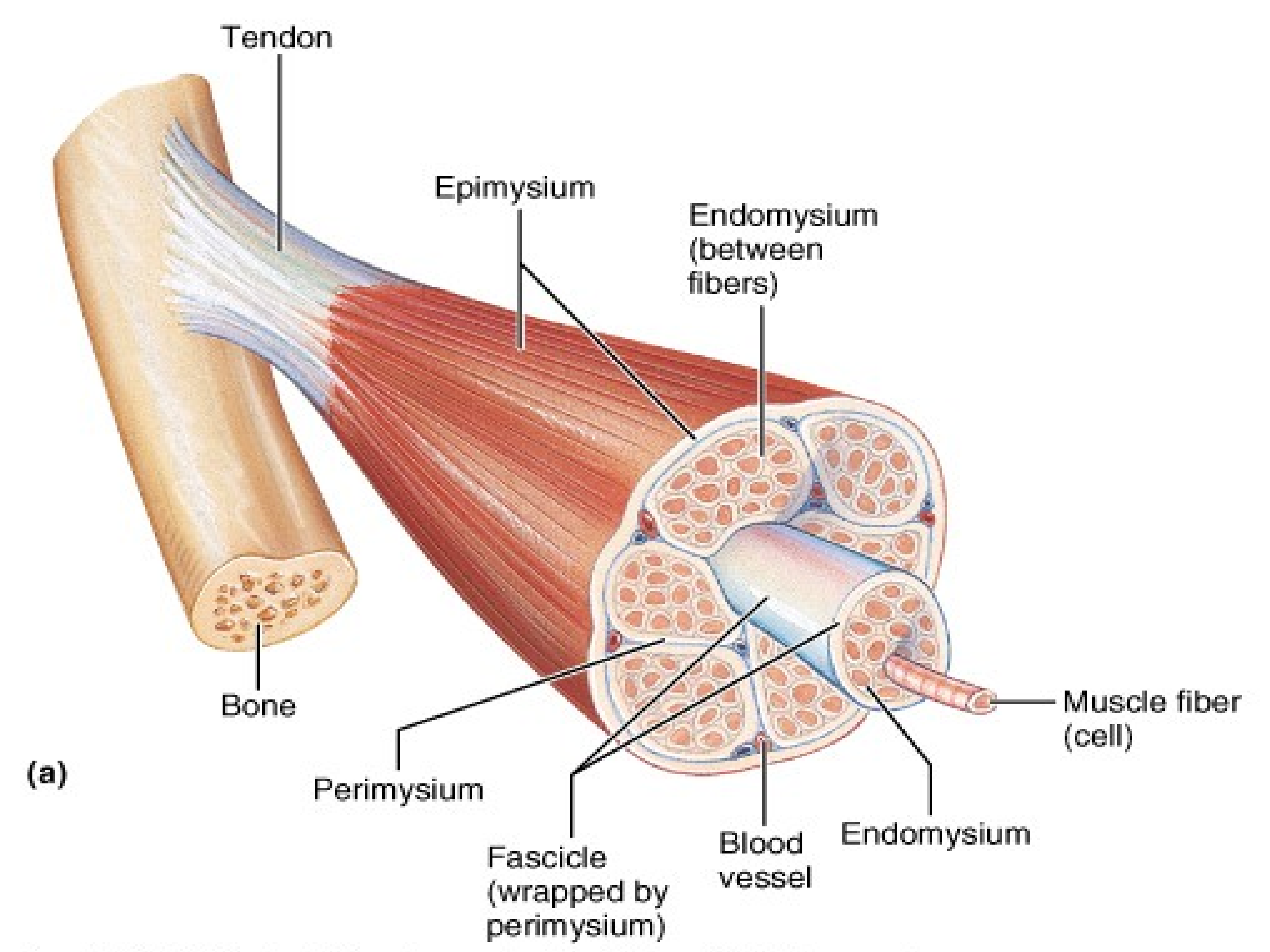
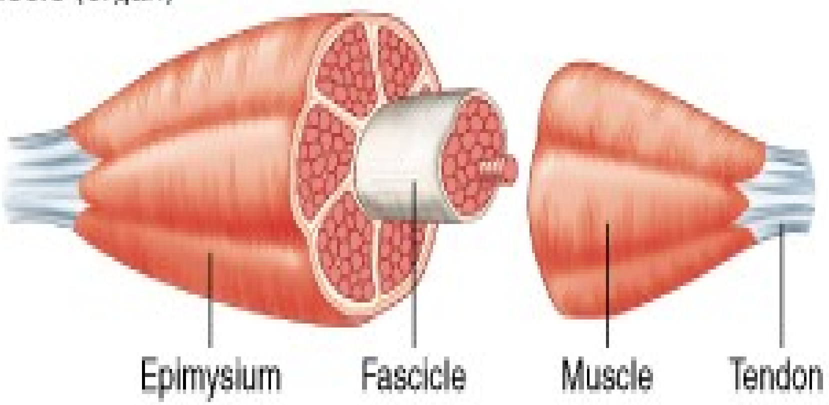
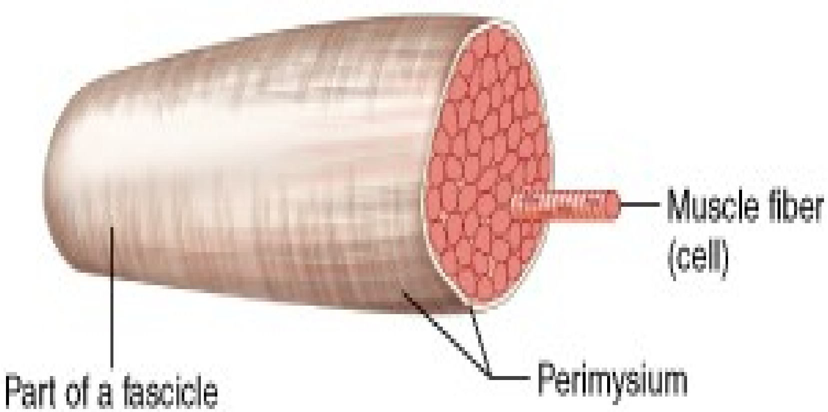
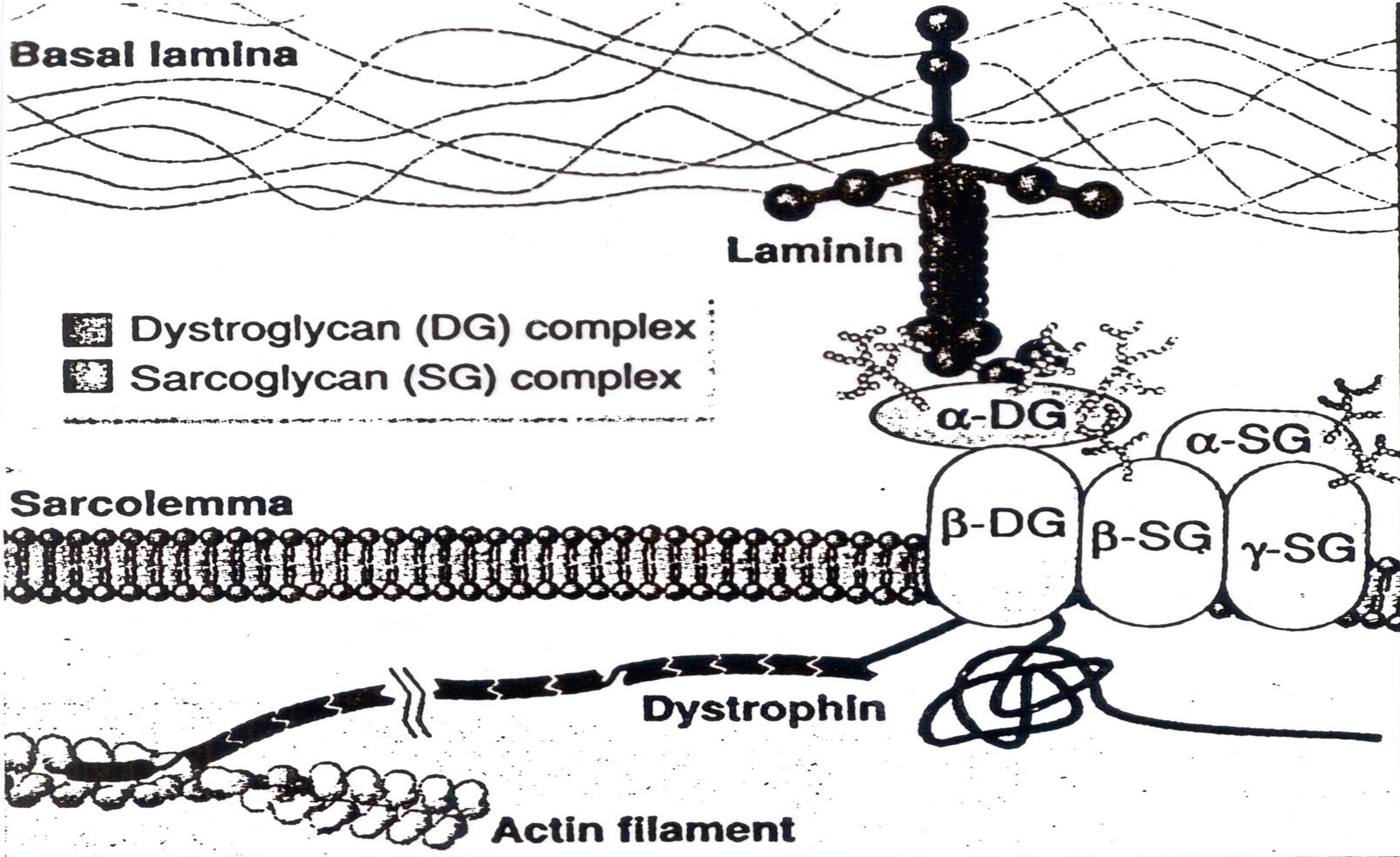
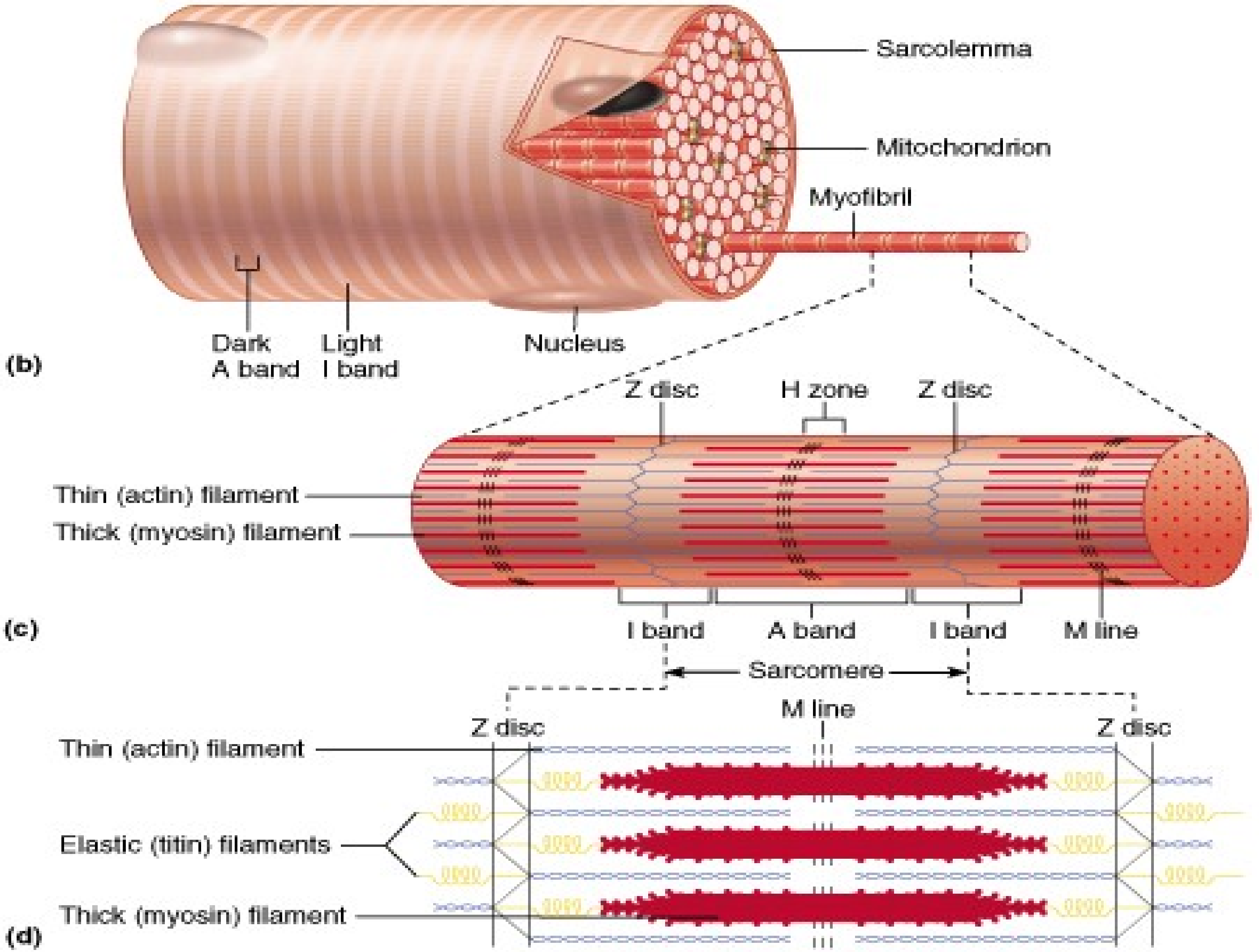

Tendon
Epimysium
Endomysium (between fibers)
Bone
Muscle fiber (cell)
(a)
Perimysium
Fascicle (wrapped by perimysium)
Blood vessel
Endomysium

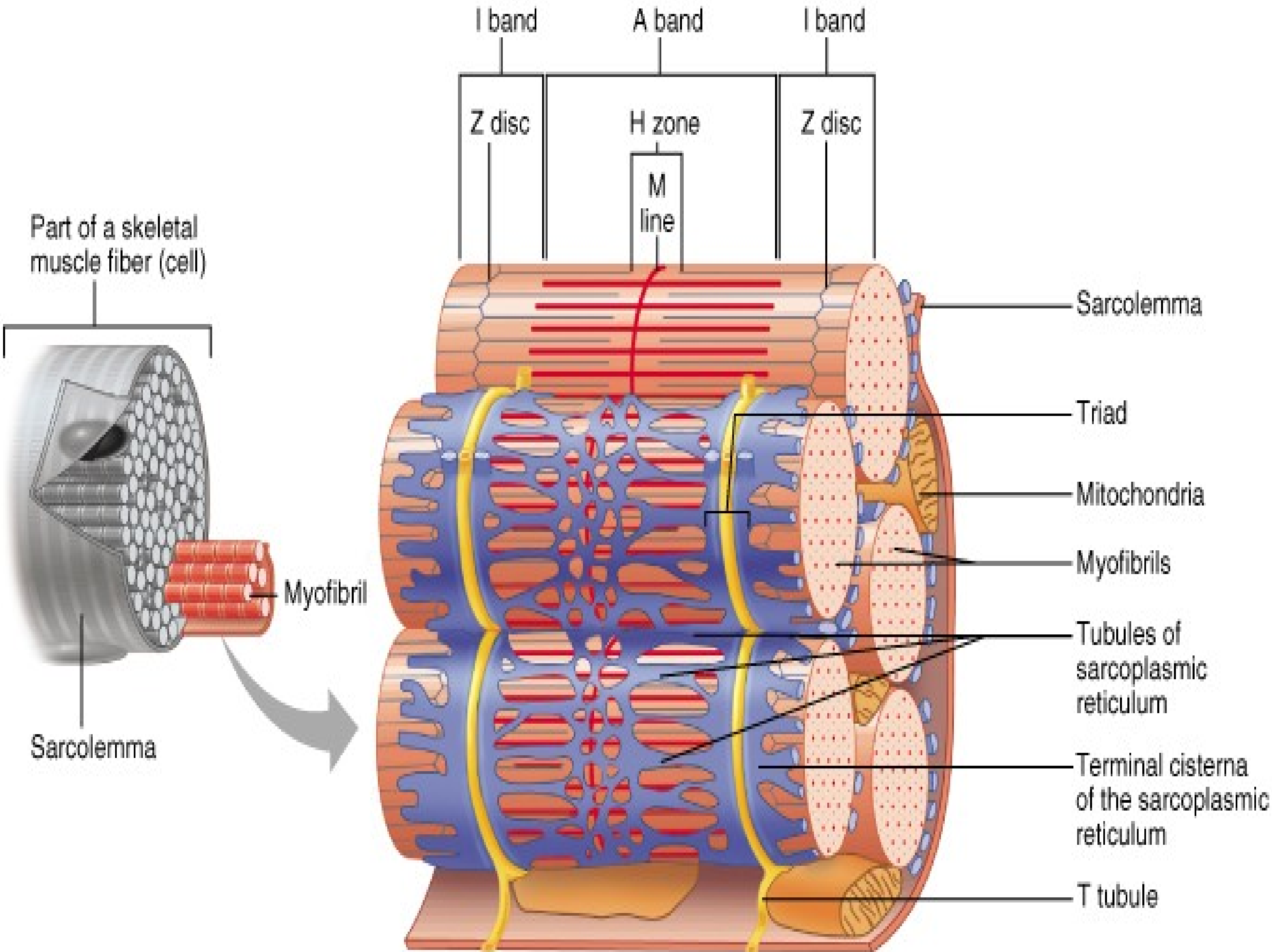
TABLE 9.1 Structure and Organizational Levels of Skeletal Muscle

Structure and organizational level	*Description*	*Connective tissue wrappings*
Muscle (organ) 	Consists of hundreds to thousands of muscle cells, plus connective tissue wrappings, blood vessels, and nerve fibers	Covered externally by the epimysium
Fascicle (a portion of the muscle) 	Discrete bundle of muscle cells, segregated from the rest of the muscle by a connective tissue sheath	Surrounded by a perimysium

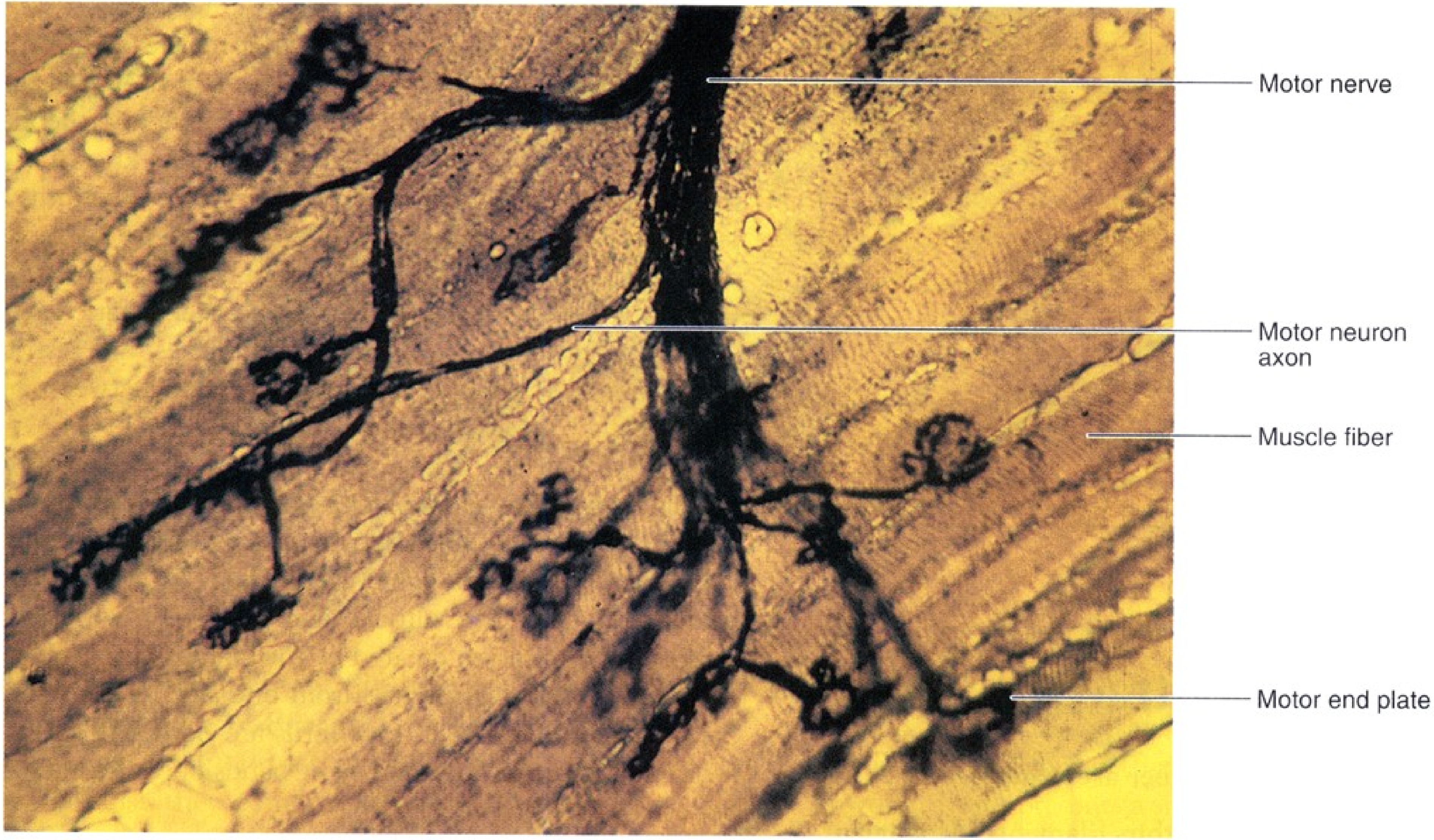


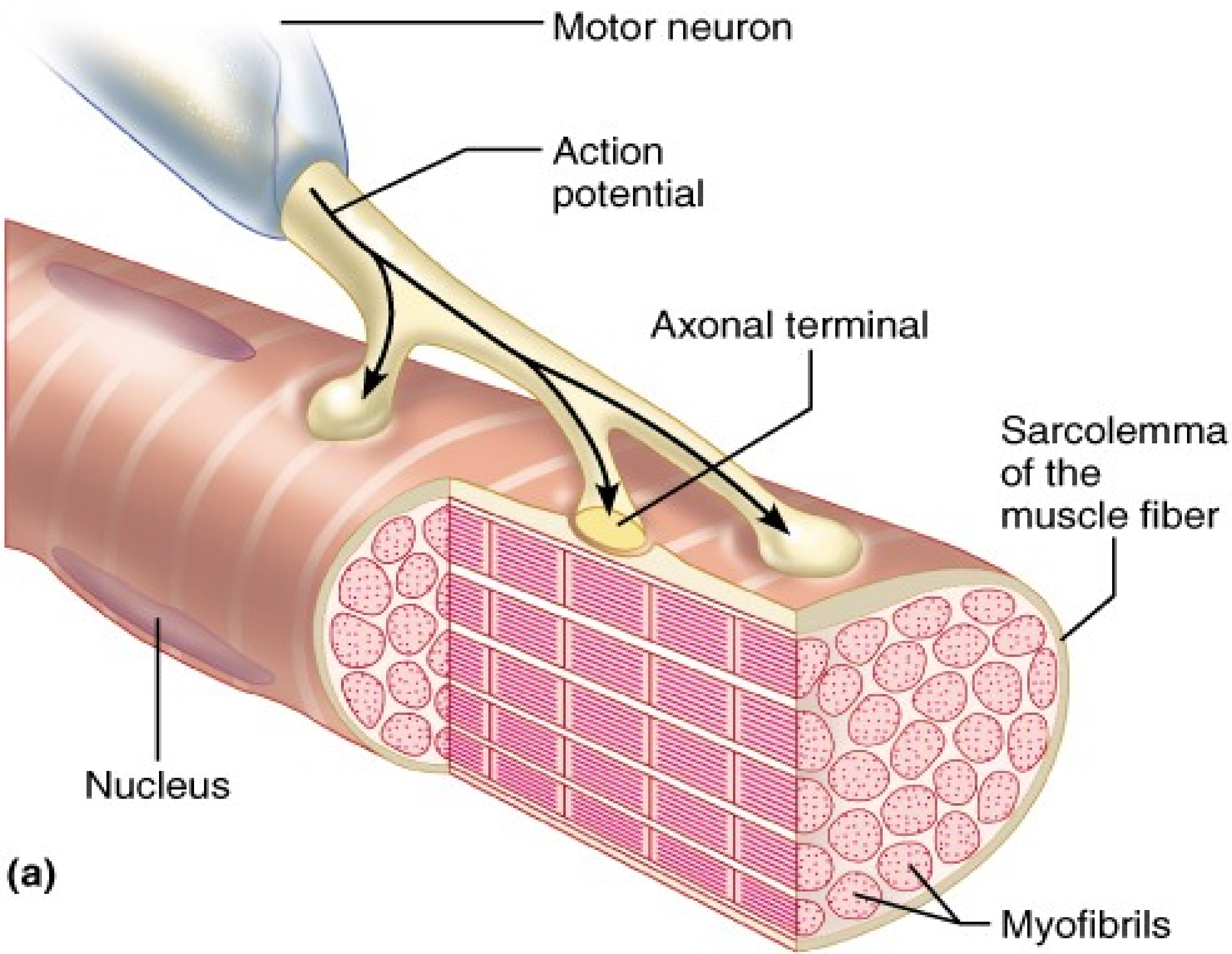
The dystrophin-glycoprotein complex. Dystrophin contacts F-actin in the cytoplasm of the cell, and the dystrophin-glycoprotein complex forms a bridge across the membrane to the merosin subunit of laminin in the extracellular matrix.


Sarcolemma
Mitochondrion
Myofibril
Dark A band
Light I band
Nucleus
(b)
Z disc
H zone
Z disc
Thin (actin) filament
Thick (myosin) filament
(c)
I band
A band
I band
M line
Sarcomere
M line
Z disc
Z disc
Thin (actin) filament
Elastic (titin) filaments
Thick (myosin) filament
(d)


I band
A band
I band
Z disc
H zone
Z disc
M line
Part of a skeletal muscle fiber (cell)
Sarcolemma
Triad
Mitochondria
Myofibrils
Myofibril
Tubules of sarcoplasmic reticulum
Terminal cisterna of the sarcoplasmic reticulum
T tubule
Sarcolemma

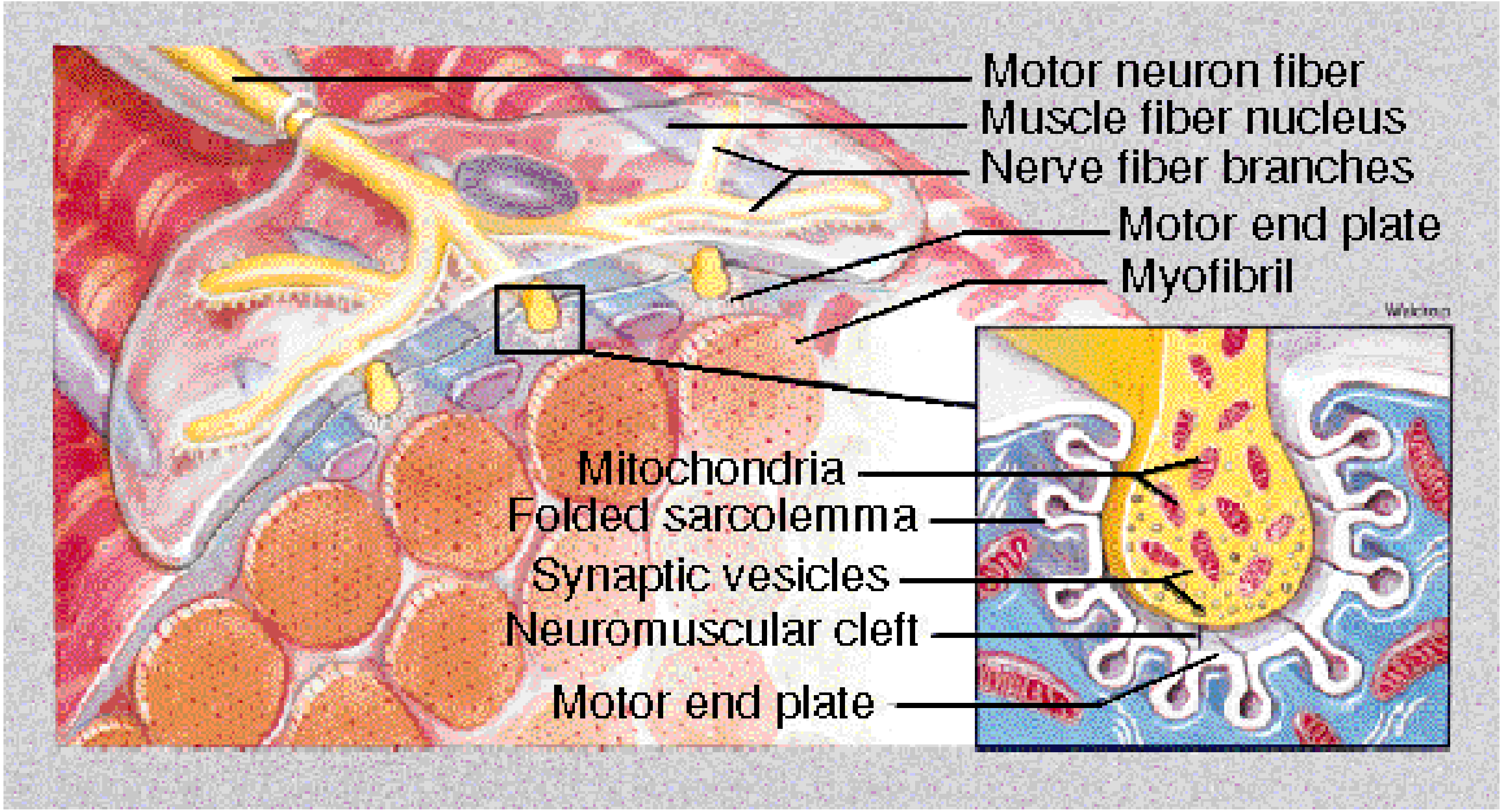
Neuromuscular Junction

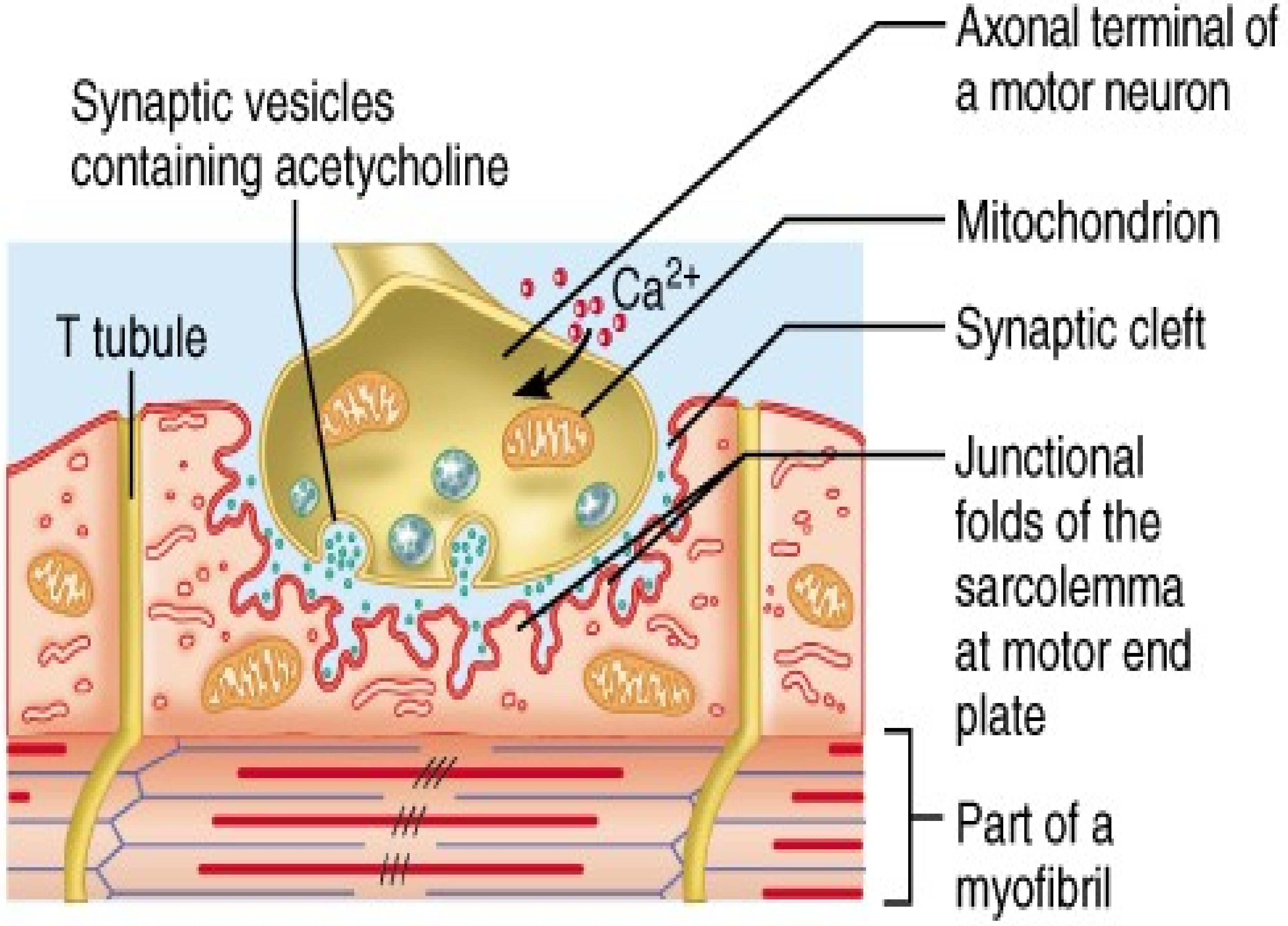

Motor nerve
Motor neuron axon
Muscle fiber
Motor end plate

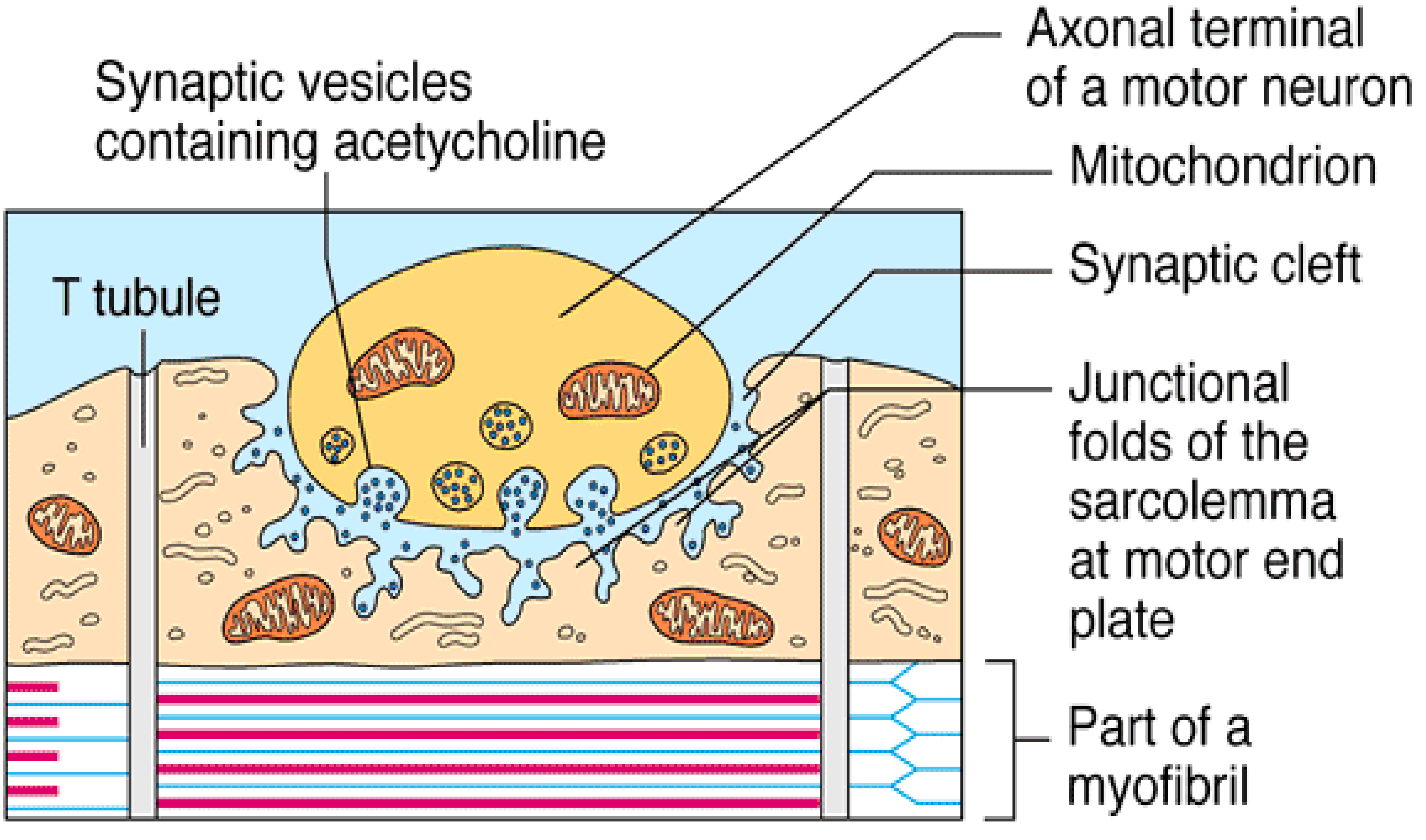


Motor neuron
Action potential
Axonal terminal
Sarcolemma of the muscle fiber
Nucleus
Myofibrils
(a)

Neuromuscular Junction. Figure 12.6a

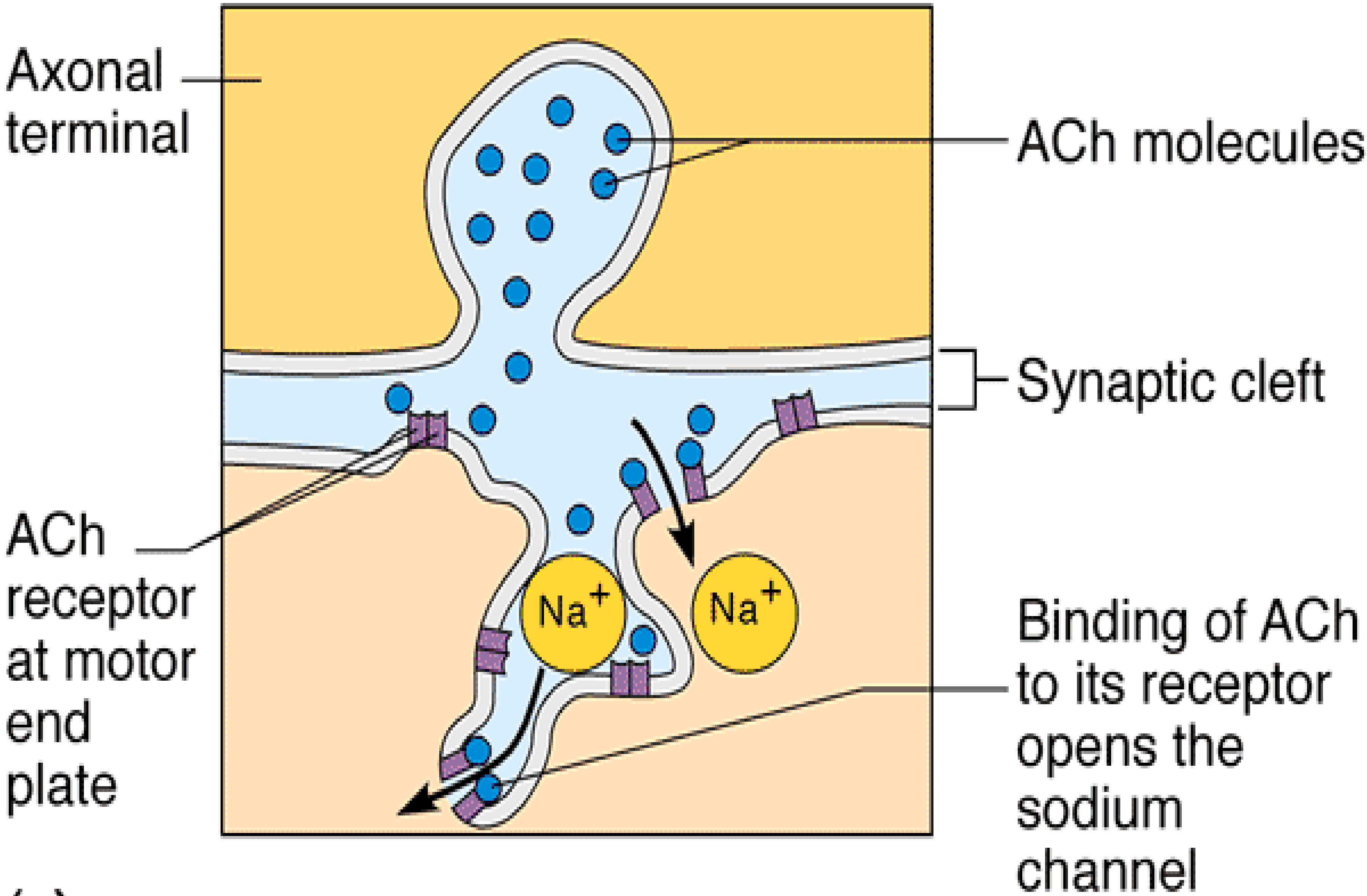



Axonal terminal of a motor neuron
Synaptic vesicles containing acetycholine
Mitochondrion
Ca^{2+}
T tubule
Synaptic cleft
Junctional folds of the sarcolemma at motor end plate
Part of a myofibril



Axonal terminal of a motor neuron
Synaptic vesicles containing acetycholine
Mitochondrion
Synaptic cleft
T tubule
Junctional folds of the sarcolemma at motor end plate
Part of a myofibril

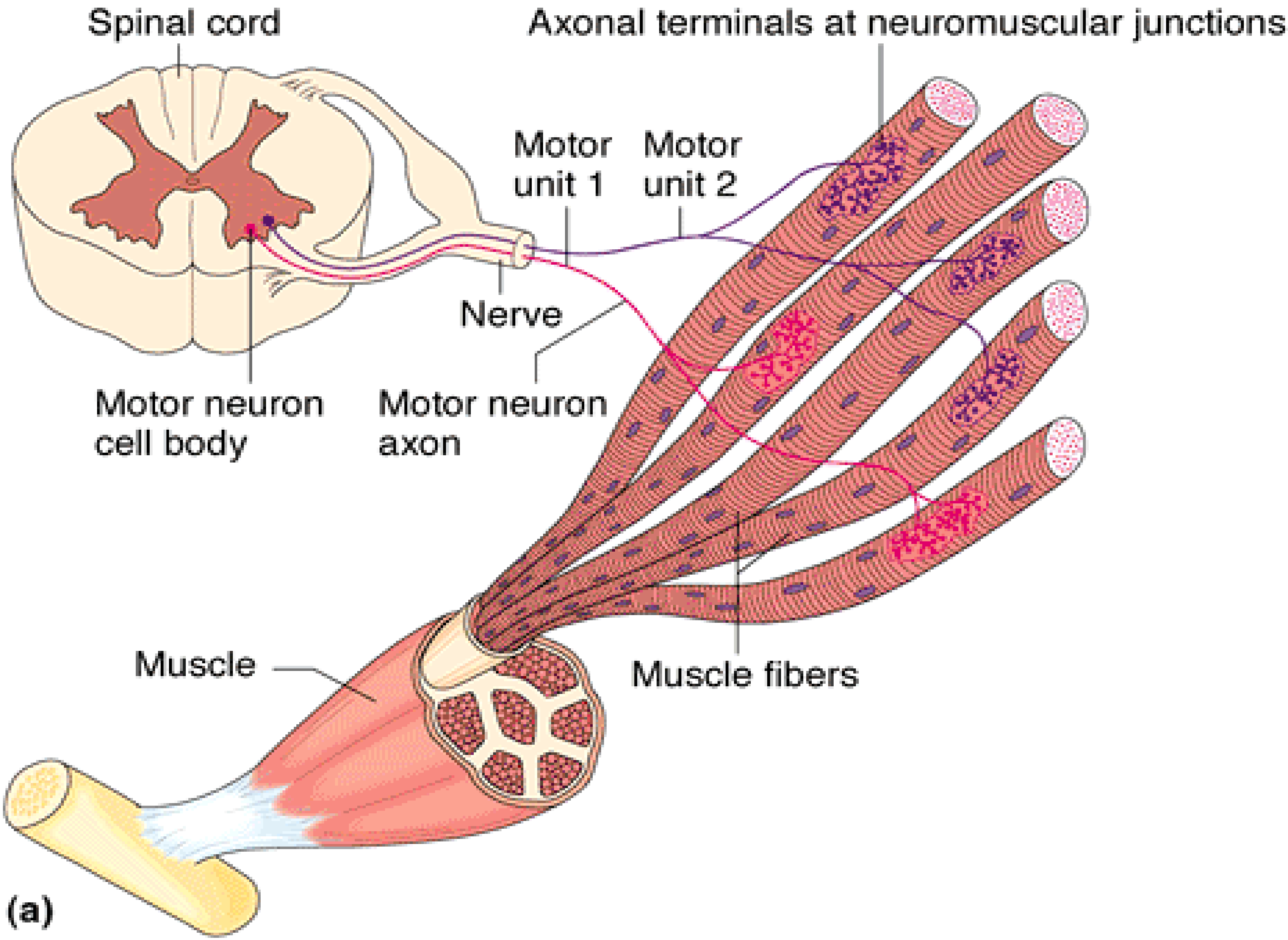
(b)

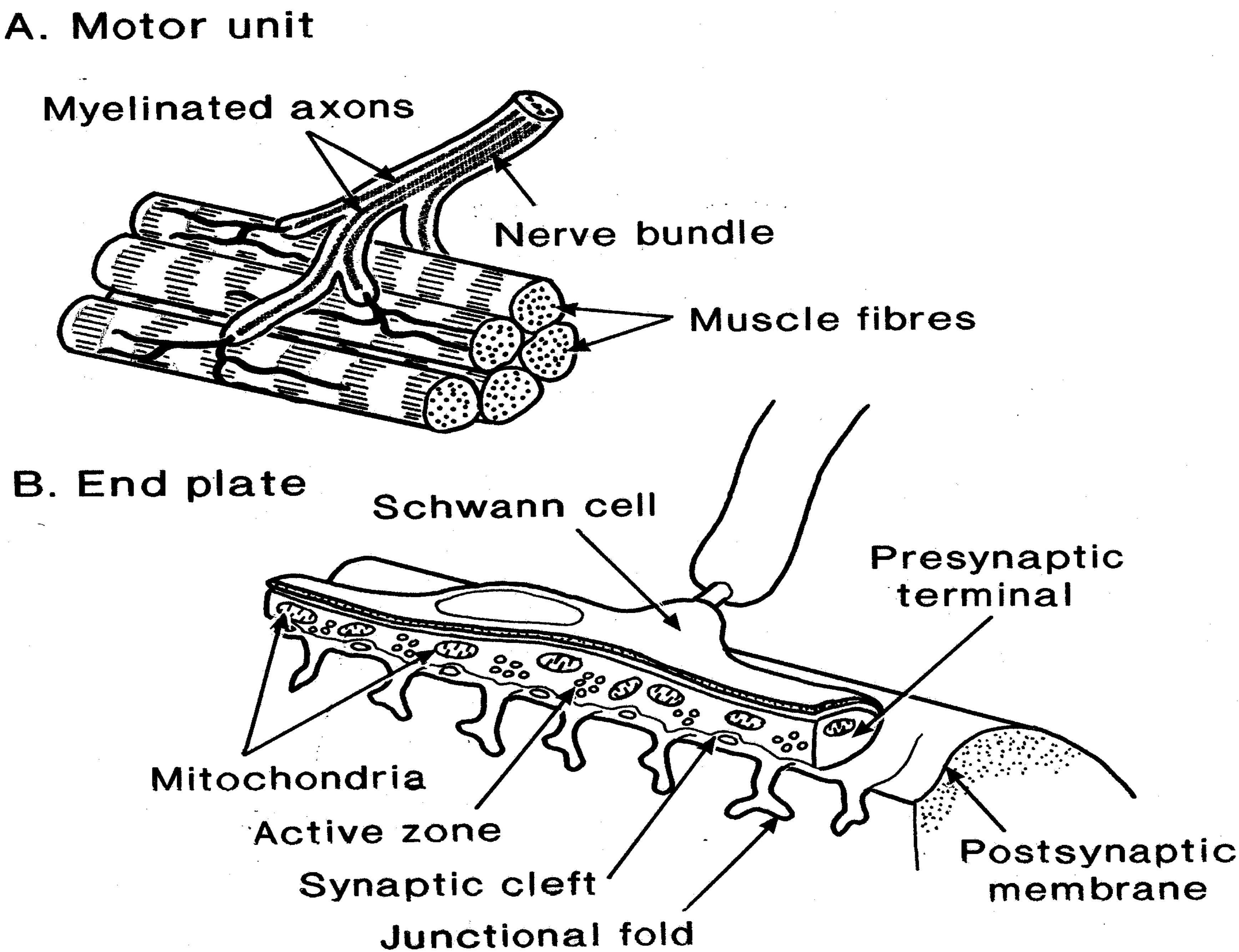

Axonal terminal
ACh molecules
Synaptic cleft
ACh receptor at motor end plate
Na+
Na+
Binding of ACh to its receptor opens the sodium channel

(c)

THE MOTOR UNIT

- Consists of:
  - One motor neuron
  - All the muscle fibers it innervates
- Ratio
  - 1:23
  - 1:2,000

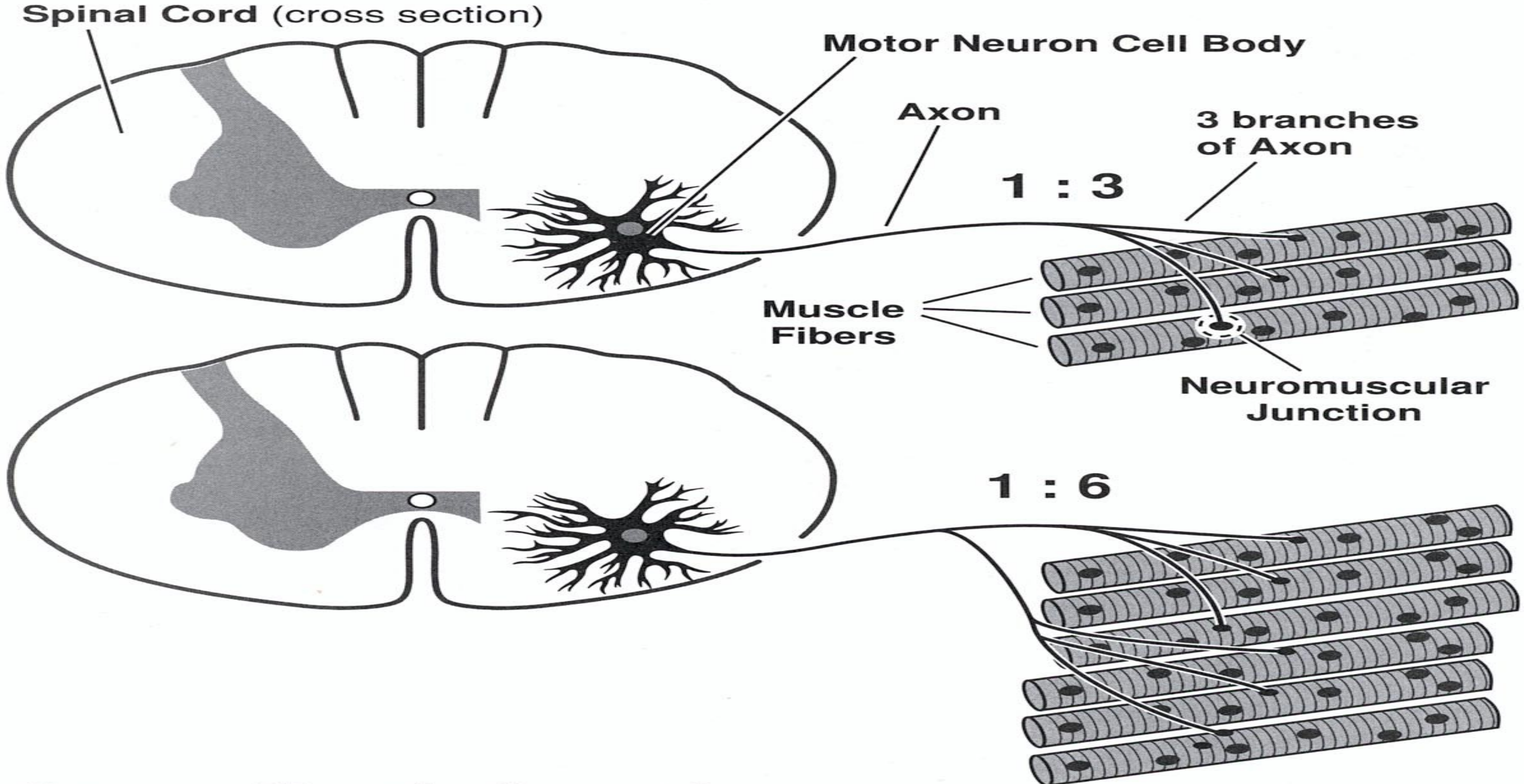

Spinal cord
Axonal terminals at neuromuscular junctions
Motor unit 1
Motor unit 2
Nerve
Motor neuron cell body
Motor neuron axon
Muscle
Muscle fibers
(a)


A. Motor unit
Myelinated axons
Nerve bundle
Muscle fibres
B. End plate
Schwann cell
Presynaptic terminal
Mitochondria
Active zone
Synaptic cleft
Junctional fold
Postsynaptic membrane

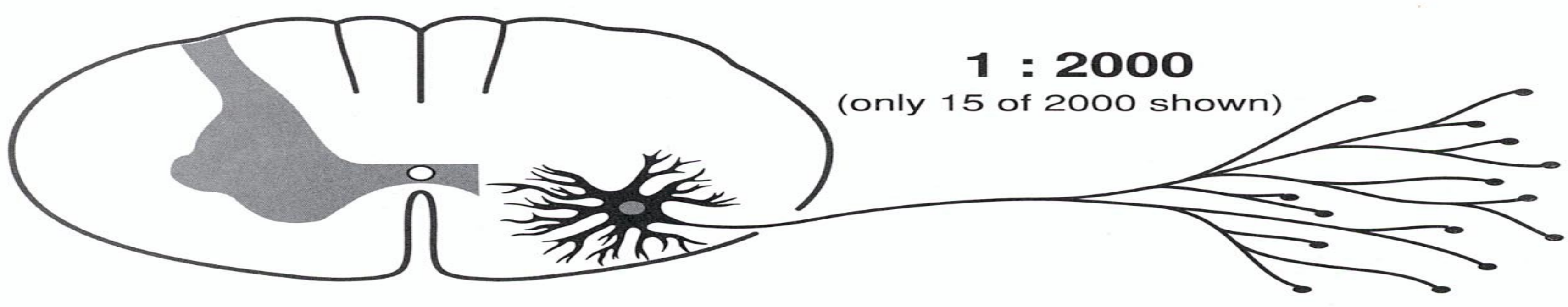
MOTOR UNITS

Motor Unit : the number of muscle fibers innervated by a single motor neuron

Fine Muscle Control



Coarse Muscle Control



MUSCLE METABOLISM

ATP Production

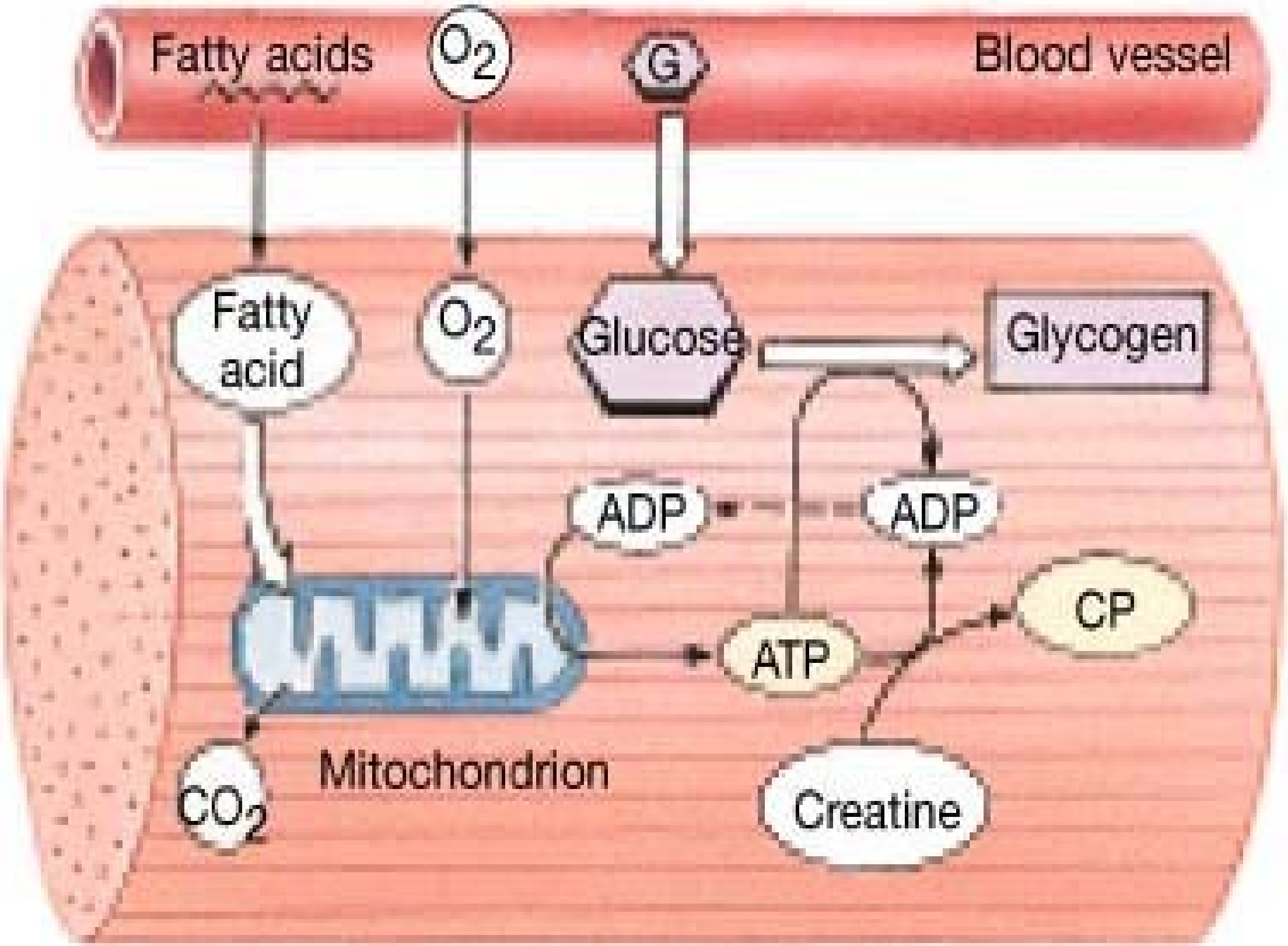
- There are 3 important sources of ATP -*(1)* *Phosphagen System : the* use of creatine phosphate and stored ATP.
  - A small amount of creatine phosphate and ATP is stored in muscle fibers for quick energy.
  - This system provides enough energy for about 15 seconds of maximal muscle activity.

ATP Production

- *(2) Glycogen-Lactic Acid System : the* conversion of glycogen or glucose into pyruvic acid or lactic acid by glycolysis. (When no oxygen is present, lactic acid is the final product.)
  - This system yields 2 molecules of ATP from each glucose molecule and provides enough energy for about 30 seconds of maximal muscle activity.
  - It is the major source of energy during a sprint.

ATP Production

- *(3) Aerobic System : the* conversion of pyruvic acid into carbon dioxide, water, and ATP.
  - It yields 36 molecules of ATP from each glucose molecule and provides energy for muscular activity lasting longer than 30 seconds. It is used during long distance running.



(a)

FIGURE 10-16 Muscle Metabolism. **(a)** A resting muscle breaks down fatty acids via aerobic respiration to make ATP. Surplus ATP is used to build reserves of creatine phosphate (CP) and glycogen.

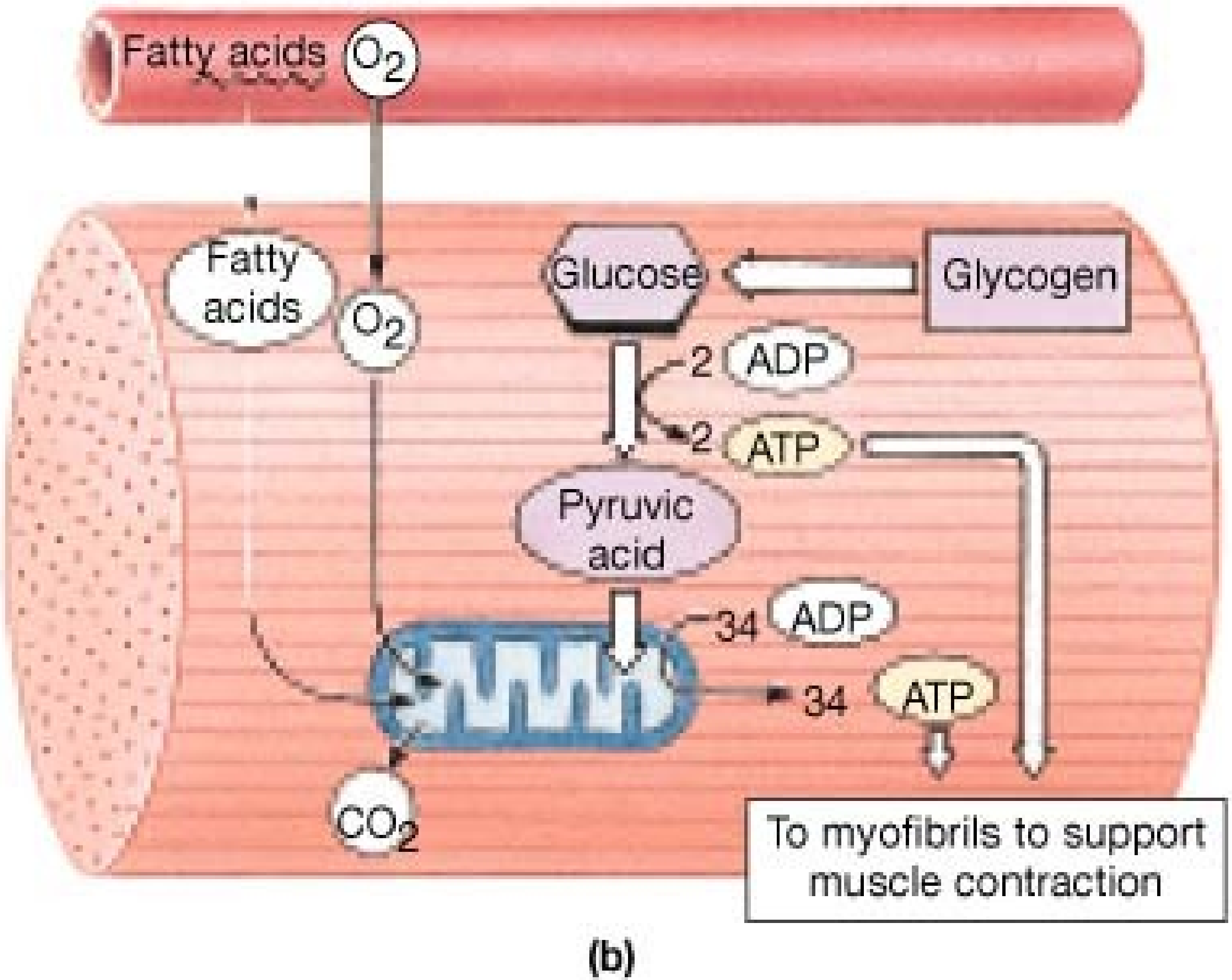
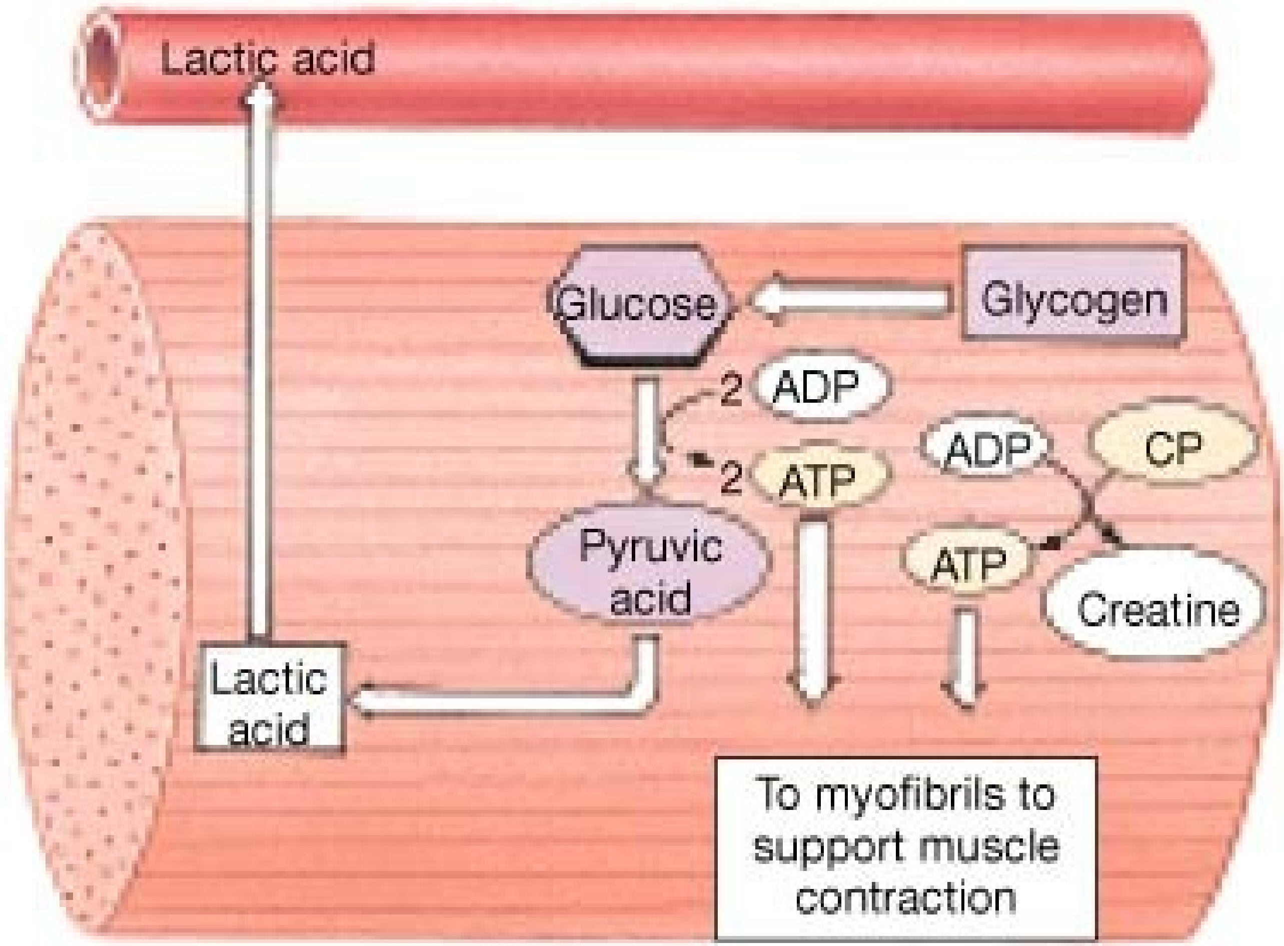


FIGURE 10-16 **Muscle Metabolism. (b)** At modest-rate activity levels, mitochondria can meet the ATP demands through aerobic metabolism of fatty acids and glucose.



(c)

FIGURE 10-16 **Muscle Metabolism.** **(c)** At peak levels of activity, the mitochondria cannot get enough oxygen to meet ATP demands. Most of the ATP is provided by glycolysis, leading to the production of lactic acid.

Heat Production (Thermogenesis)

- As much as 85% of the energy produced by cellular respiration during muscle contraction is released as heat.

Recovery Oxygen Consumption (Oxygen Debt)

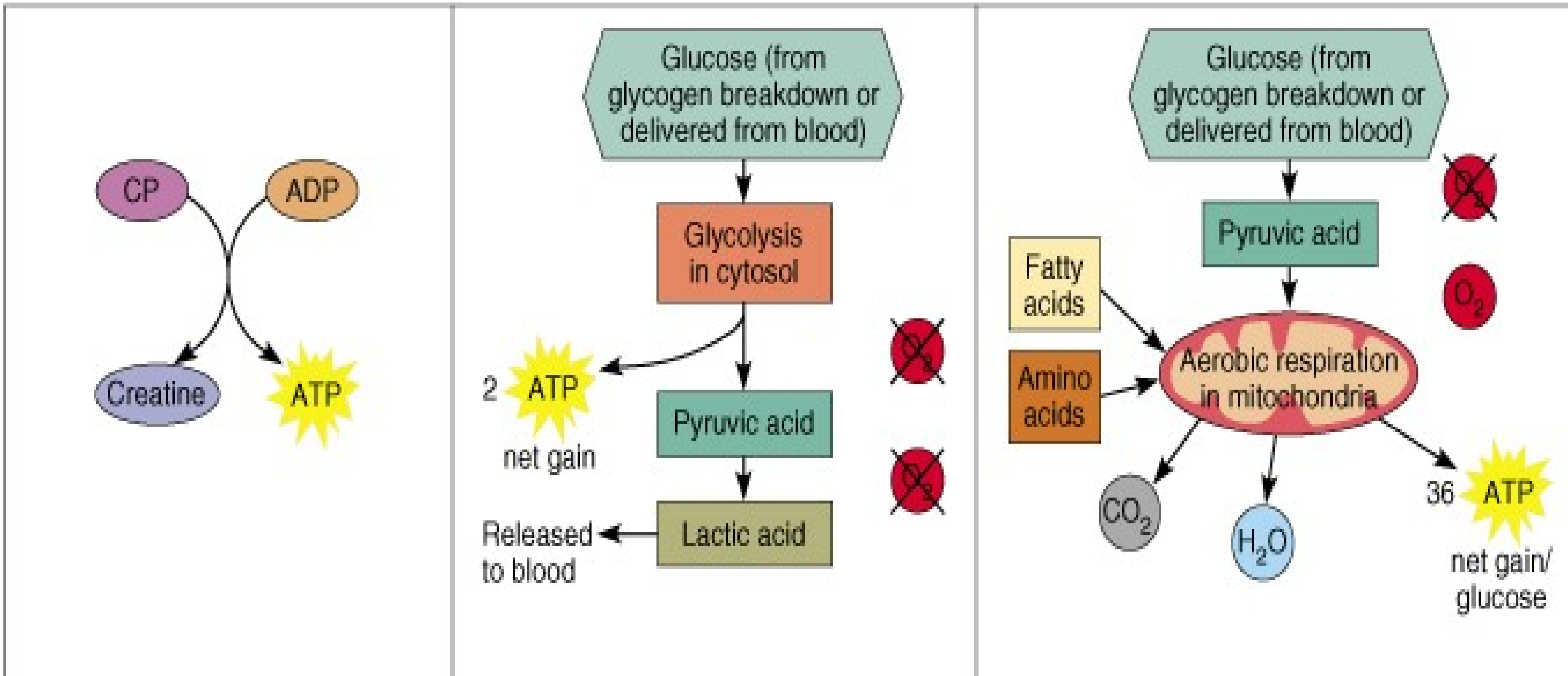
- The elevated oxygen intake after exercise (panting) is needed for the following uses
  - (1) Conversion of **lactic acid** back into **pyruvic acid**.
  - (2) Re-establishment of **glycogen** stores in muscle cells and liver cells.

Recovery Oxygen Consumption (Oxygen Debt)

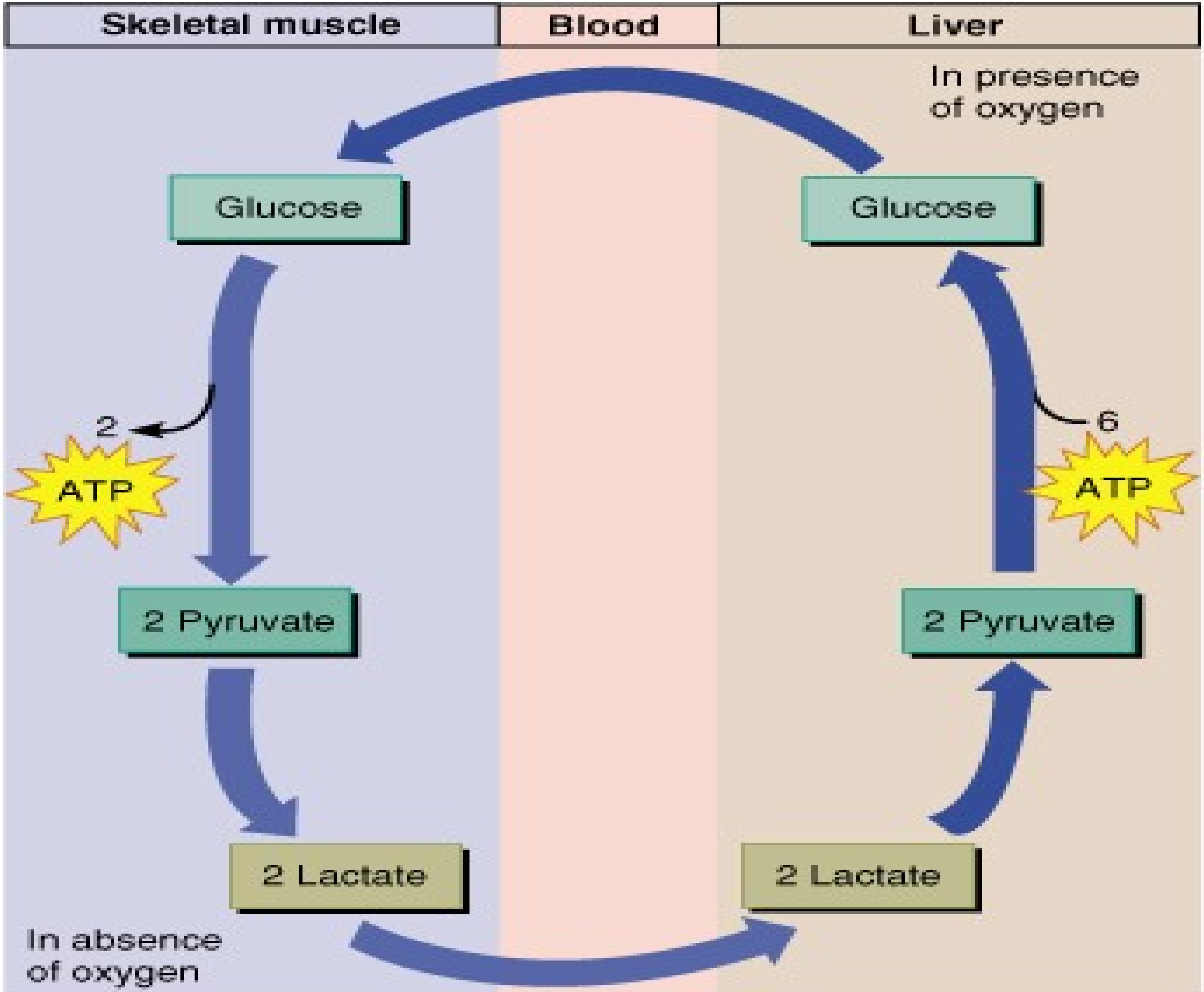
- (3) Resynthesis of **creatine phosphate** and **ATP** stored in muscle cells.
- (4) Replacement of oxygen removed from **myoglobin** (oxygen-storing protein in muscle cells).
- (5) ATP production for metabolic reactions (increased rate due to increased body temperature).

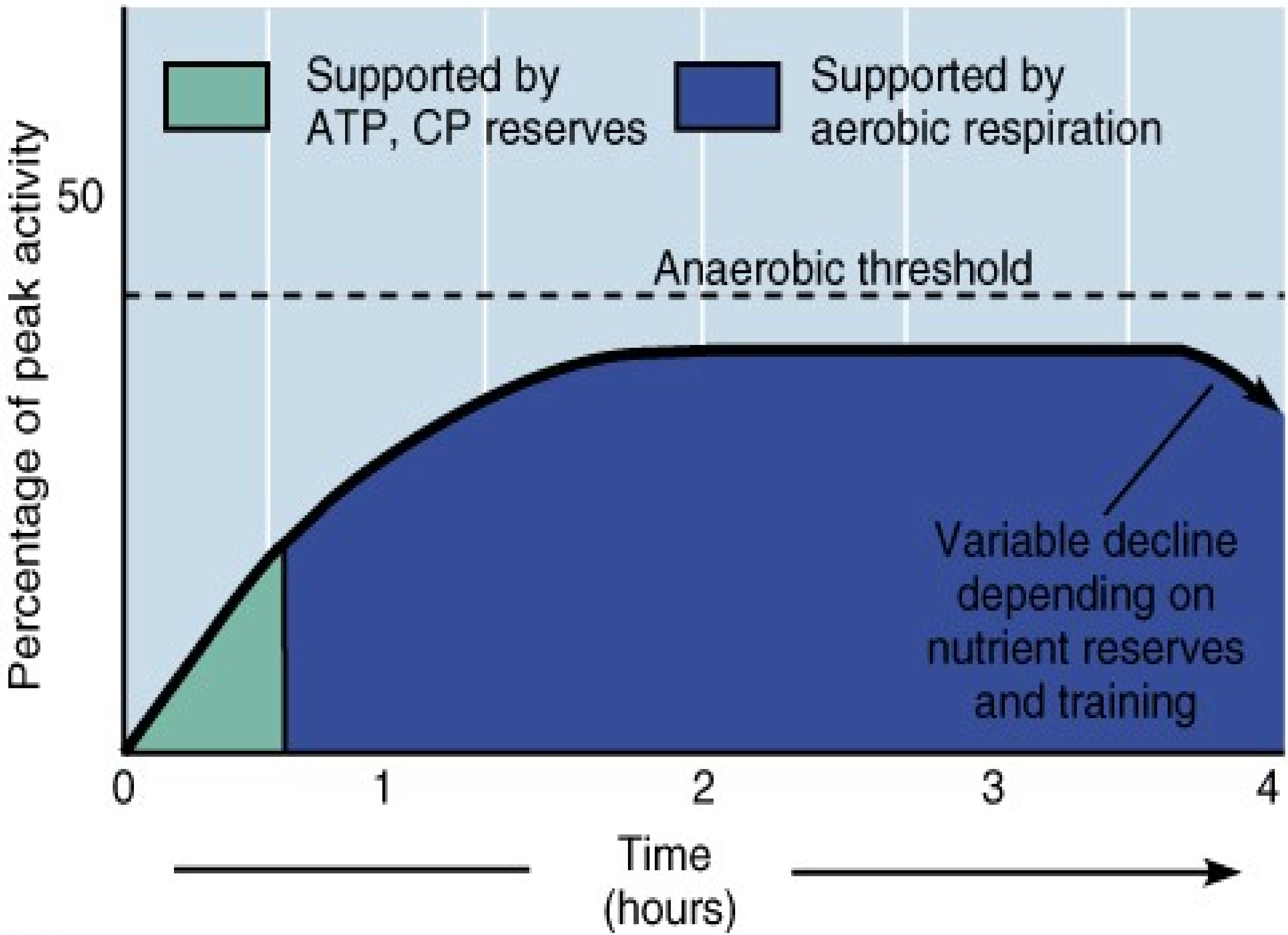
Recovery Oxygen Consumption (Oxygen Debt)

- (6) ATP production for the continuing elevated activity of cardiac and skeletal muscles.
- (7) ATP production needed for an increased rate of tissue repair.

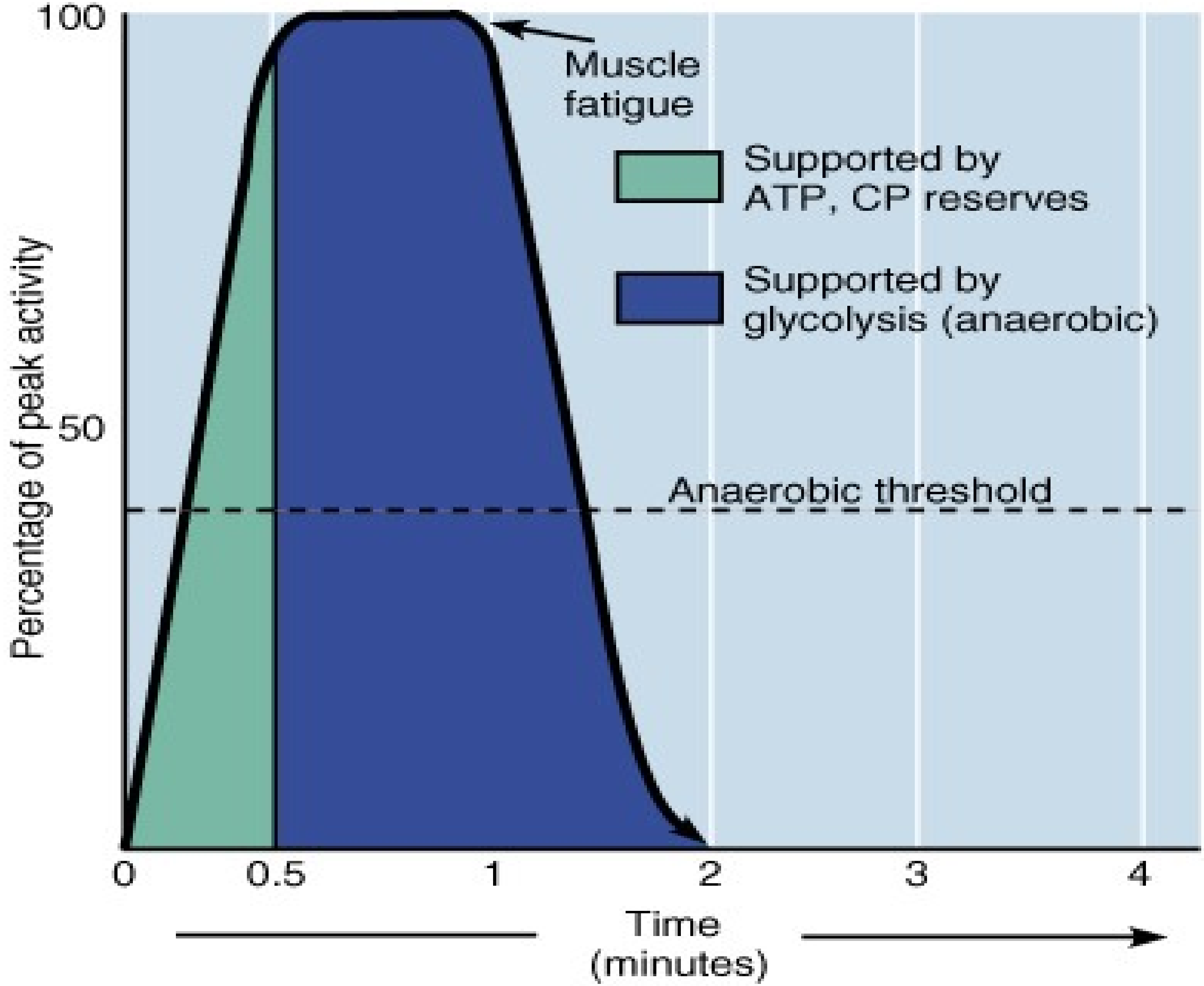


(a) Direct phosphorylation (coupled reaction of creatine phosphate [CP] and ADP)	**(b) Anaerobic mechanism (glycolysis and lactic acid formation)**	**(c) Aerobic mechanism (oxidative phosphorylation)**
Energy source: CP	Energy source: glucose	Energy source: glucose; pyruvic acid; free fatty acids from adipose tissue; amino acids from protein catabolism
Oxygen use: None Products: 1 ATP per CP, creatine Duration of energy provision: 15 sec.	Oxygen use: None Products: 2 ATP per glucose, lactic acid Duration of energy provision: 30–60 sec.	Oxygen use: Required Products: 36 ATP per glucose, CO_2, H_2O Duration of energy provision: Hours


Skeletal muscle
Blood
Liver
In presence of oxygen
Glucose
Glucose
2
ATP
6
ATP
2 Pyruvate
2 Pyruvate
2 Lactate
2 Lactate
In absence of oxygen



Supported by ATP, CP reserves
Supported by aerobic respiration
Percentage of peak activity
50
Anaerobic threshold
Variable decline depending on nutrient reserves and training
0
1
2
3
4
Time (hours)


100
50
Percentage of peak activity
Muscle
fatigue
Supported by
ATP, CP reserves
Supported by
glycolysis (anaerobic)
Anaerobic threshold
0
0.5
1
2
3
4
Time
(minutes)

Fatigue

- Inability of a muscle to maintain its strength of contraction or tension results from **insufficient ATP production**. Factors that contribute to fatigue include:
  - (1) Insufficient **oxygen** delivered to muscle cells.
  - (2) Depletion of **glycogen** stored in muscle cells.
  - (3) Buildup of **lactic acid** in body fluids.

Fatigue

- (4) Insufficient **acetylcholine** released by synaptic end bulbs of motor neurons.
- (5) Unexplained mechanisms in the brain.

CONTRACTION
OF
SKELETAL MUSCLE

MYOGRAM

- A laboratory method to study and record muscle activity, which uses an electrical shock(s) to simulate nerve impulse(s)

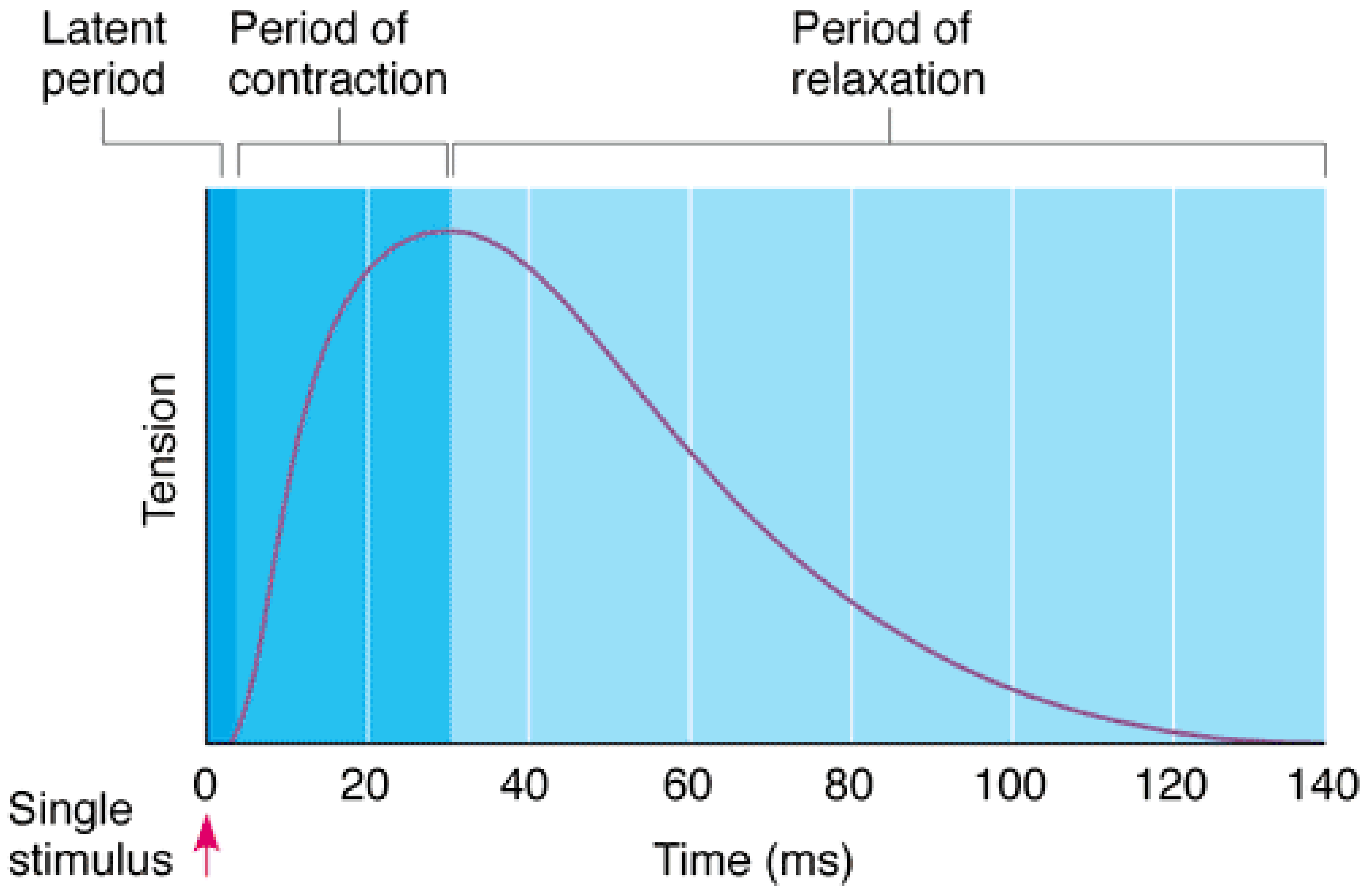
- A graphic recording of mechanical contractile activity

MYOGRAM

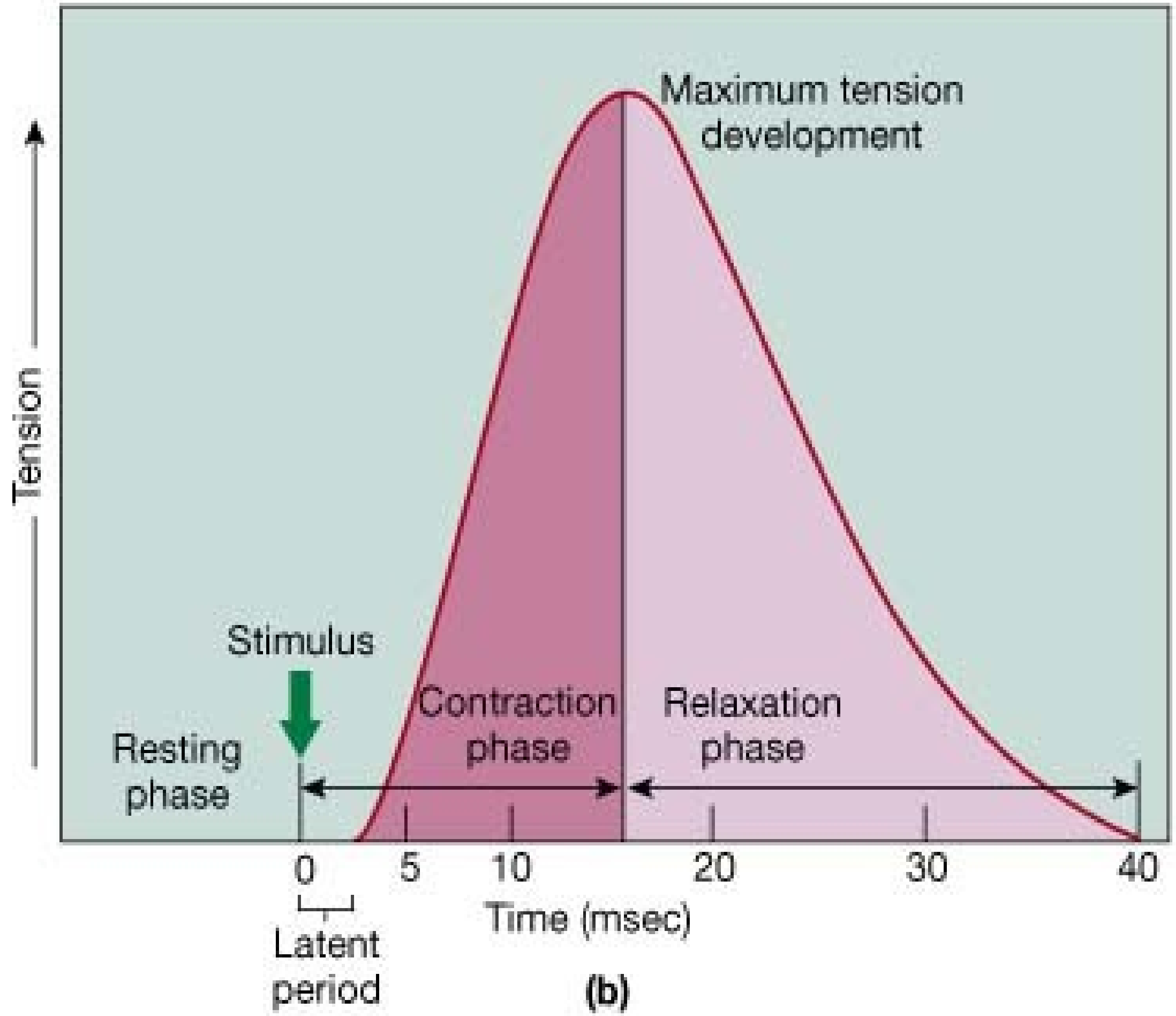
- A electrical shock is applied resulting in a brief **threshold** stimulus - a **muscle twitch**
- A twitch may be strong or weak depending upon the number of motor units activated.

MYOGRAM

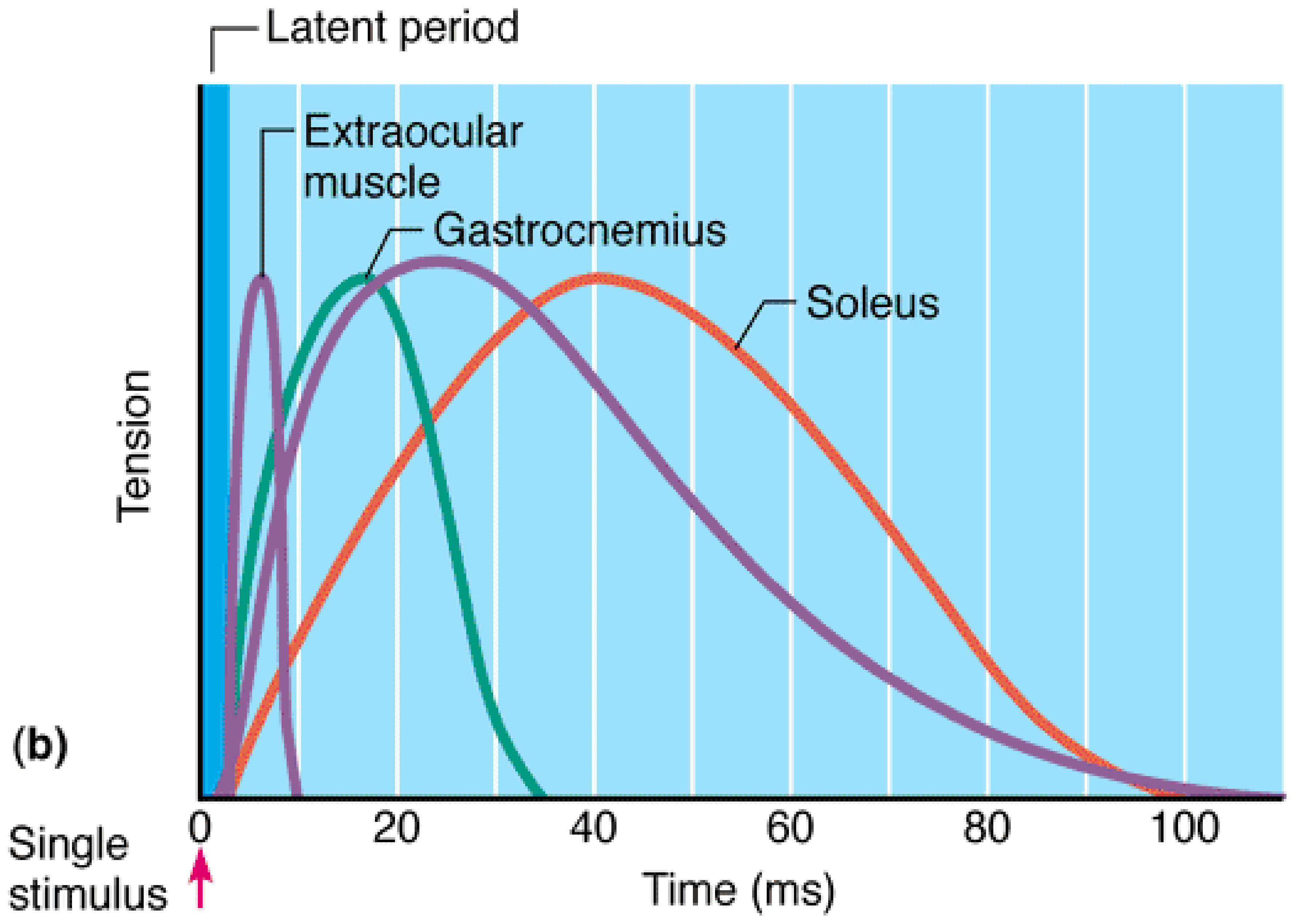
- Latent peroid - 1st few ms following stimulation when excitation-contraction coupling is occurring
- Contraction period - when cross bridges are active. If the tension (pull) overcomes the resistance of the load, the muscle shortens
- Relaxation period - reentry of Ca^{2+} into SR


Latent period
Period of contraction
Period of relaxation
Tension
0
20
40
60
80
100
120
140
Single stimulus
Time (ms)

(a)



• ***FIGURE 10-10*** **The Twitch and Development of Tension.** **(b)** Details of the time course of a single twitch contraction in the gastrocnemius muscle. Note the presence of a latent period, which corresponds to the time needed for the conduction of action potential and the subsequent release of calcium ions by the sarcoplasmic reticulum.


Latent period
Extraocular muscle
Gastrocnemius
Soleus
Tension
(b)
0
20
40
60
80
100
Single stimulus
Time (ms)

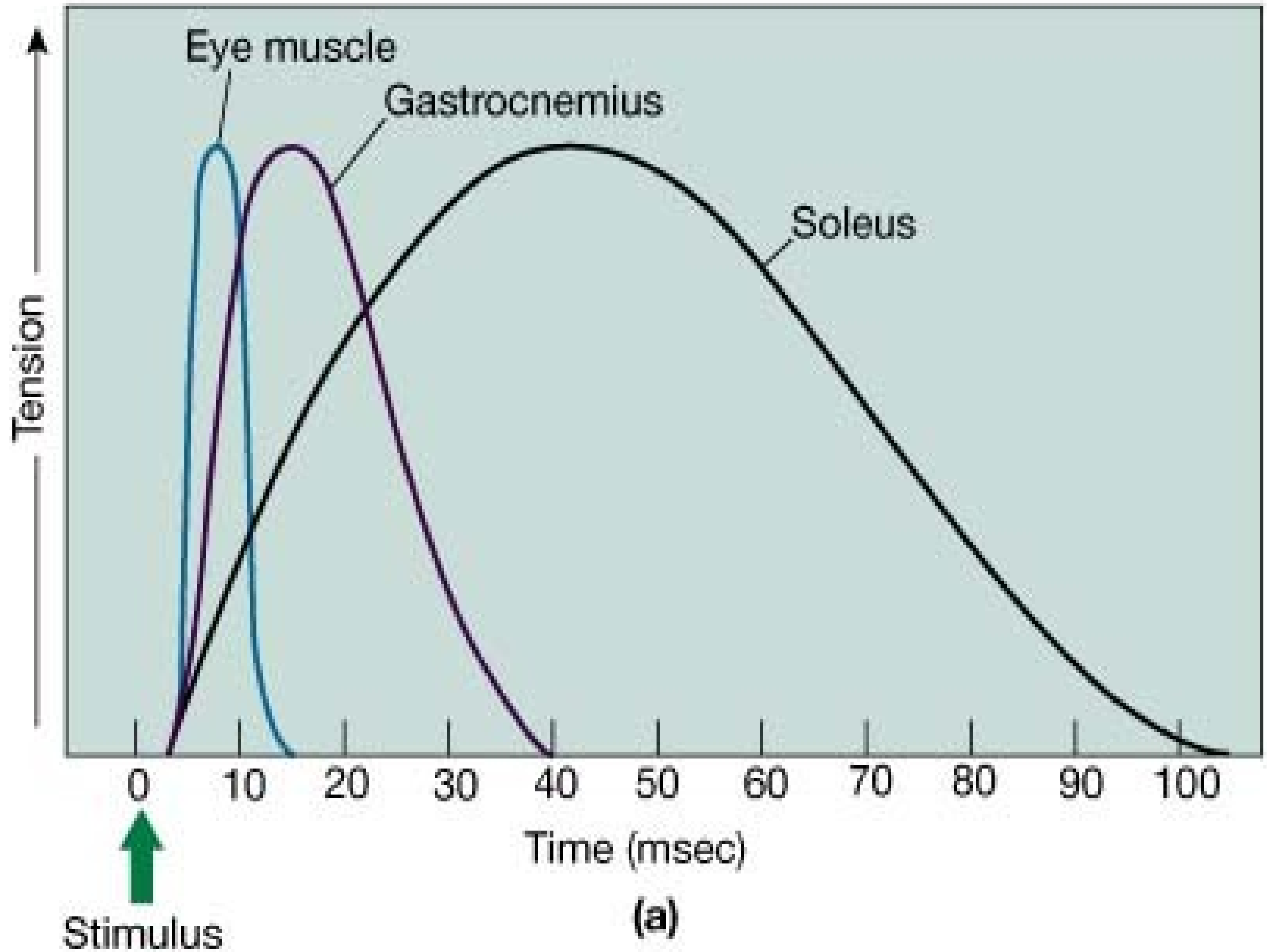


FIGURE 10-10 **The Twitch and Development of Tension.** **(a)** Myogram showing differences in the time course of a twitch contraction in different skeletal muscles in the body.

TYPES OF SKELETAL MUSCLE CONTRACTIONS

- Twitch
- Summation
- Tetanus
- Treppe
- Isotonic contraction (same strength)
- Isometric contraction (same length)

Wave Summation

- Muscles response to frequency of stimulation in rapid succession - appearing to ride on the shoulders of the first contraction.
- the 2nd contraction occurs before the muscle has completely relaxed
- 2nd is stronger than the 1st = summed.

Tetanus

- If the stimulus is held constant & the muscle is stimulated at an increasingly faster rate, **Ca^{2+}** concentration increases, progressing to a sustained but quivering contraction - unfused tetanus
- Finally, all evidence of relaxation disappears - fused tetanus

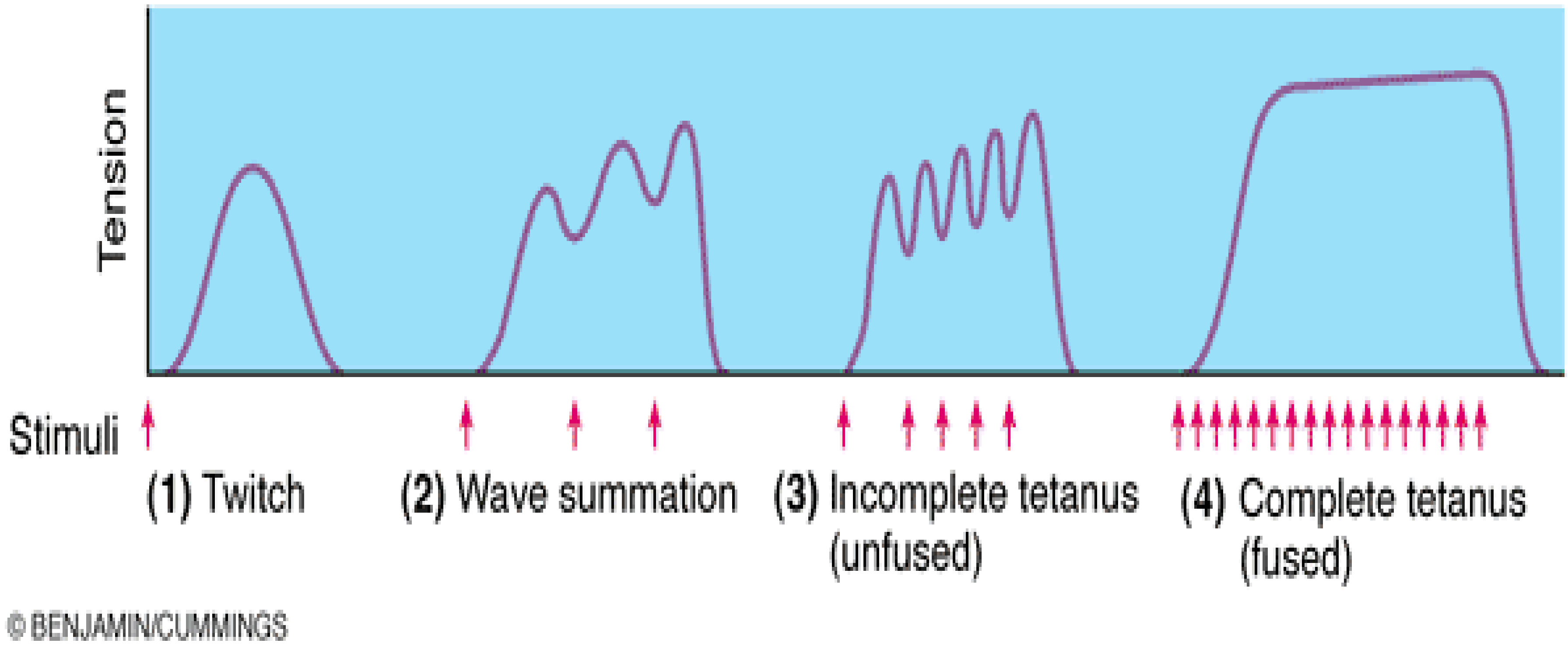
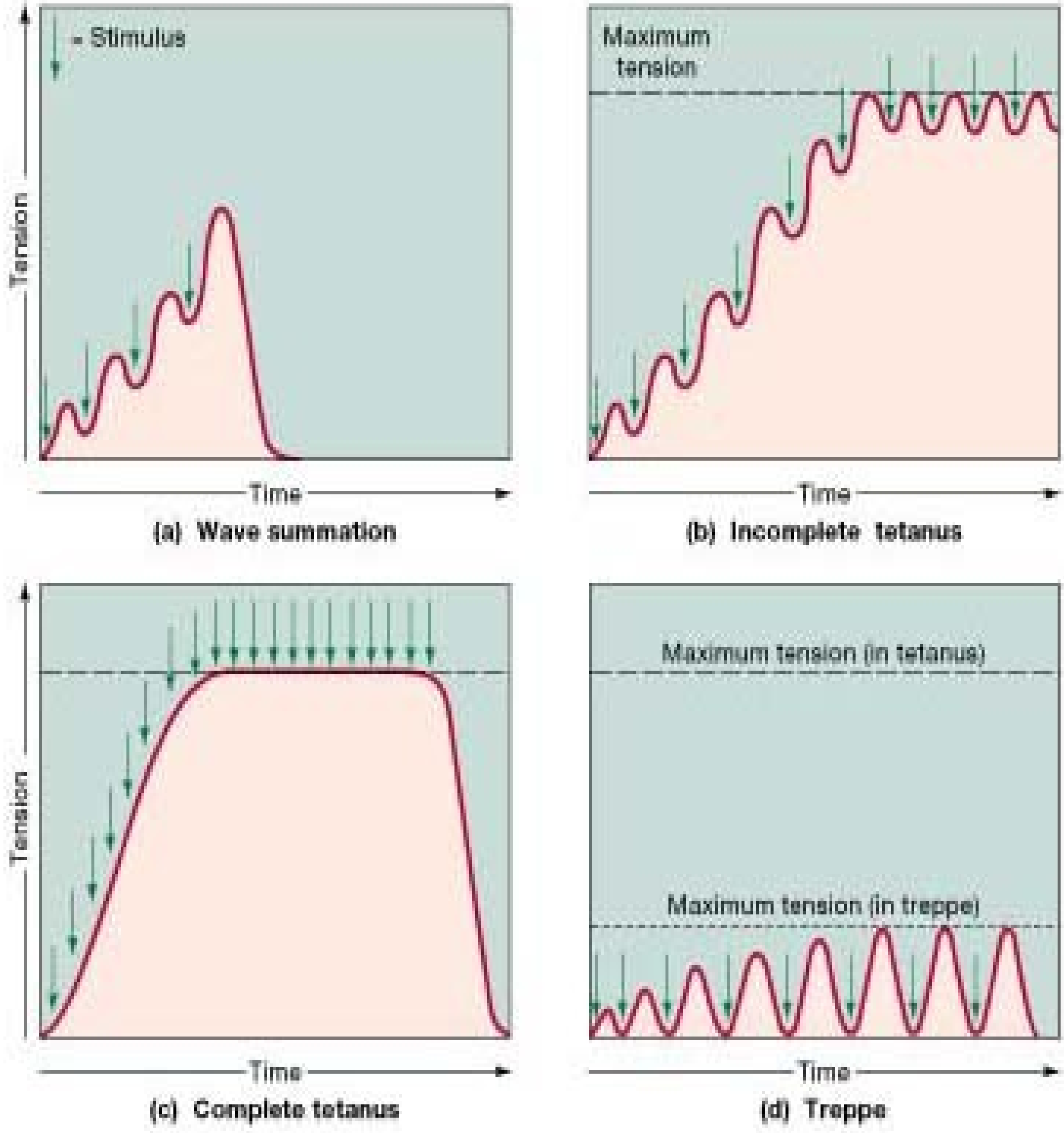
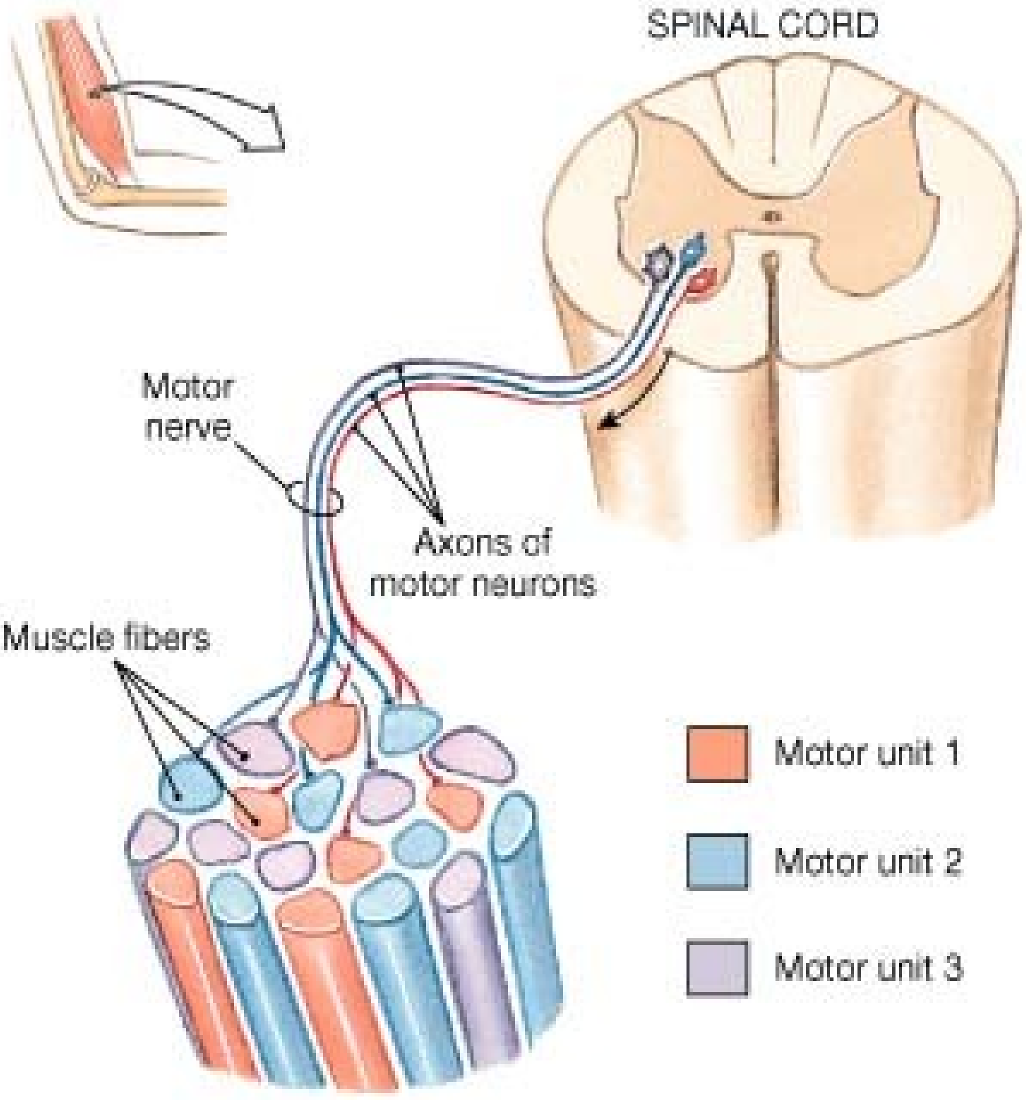

Tension
Stimuli
(1) Twitch
(2) Wave summation
(3) Incomplete tetanus (unfused)
(4) Complete tetanus (fused)
© BENJAMIN/CUMMINGS

FIGURE 10-11 Effects of Repeated Stimulations. **(a)** Wave summation occurs when successive stimuli arrive before relaxation (the downturn of the curve) has been completed. **(b)** Incomplete tetanus occurs if the rate of stimulation increases further. Tension production will rise to a peak, and the periods of relaxation will be very brief. **(c)** During complete tetanus, the frequency of stimulation is so high that the relaxation phase has been entirely eliminated and tension plateaus at maximal levels. **(d)** Treppe is an increase in peak tension following repeated stimuli delivered shortly after the completion of the relaxation phase of each twitch.



Recruitment

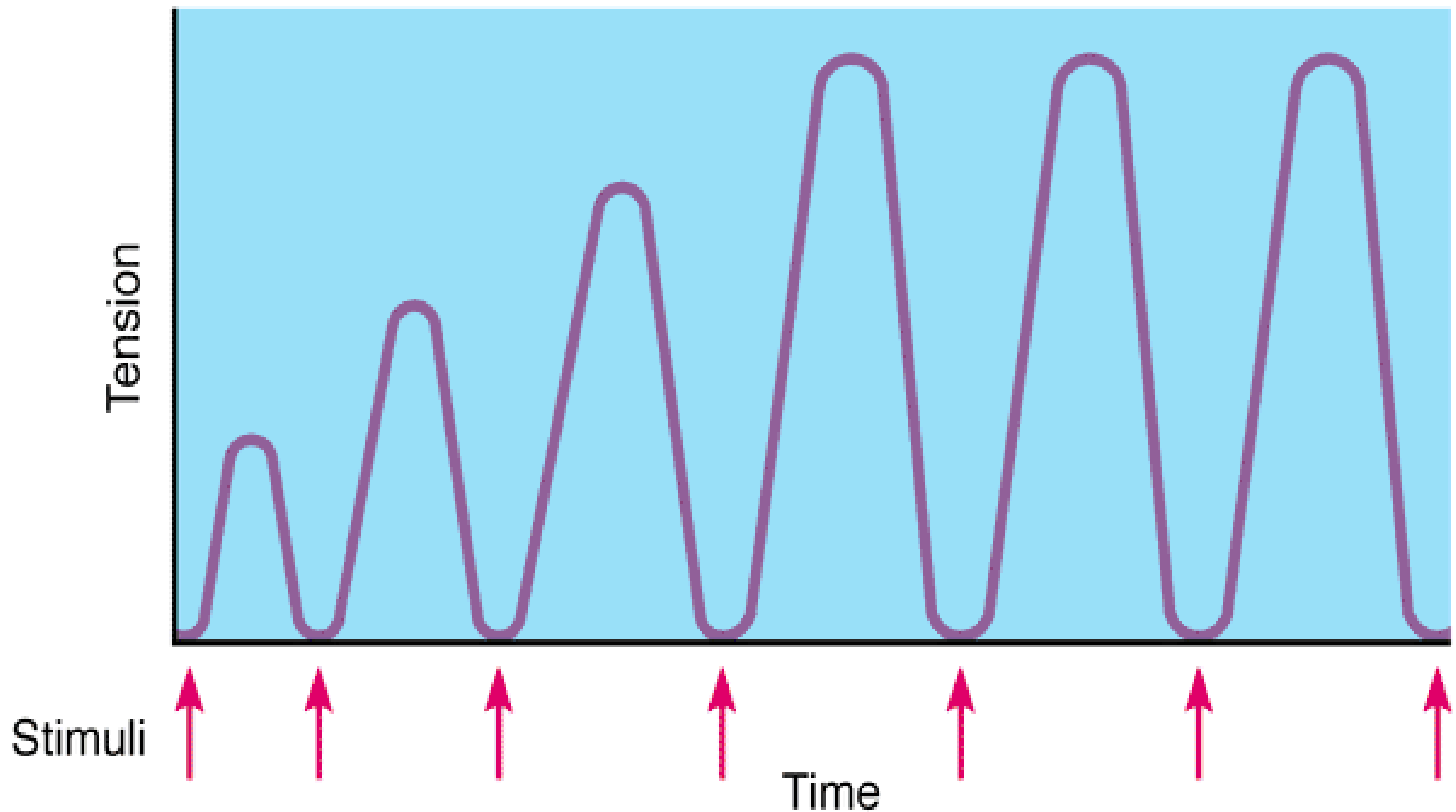
- The force of contraction is controlled more precisely by multiple **motor unit** summation, which is achieved by recruiting more and more motor units, resulting in more muscle fibers contracting.



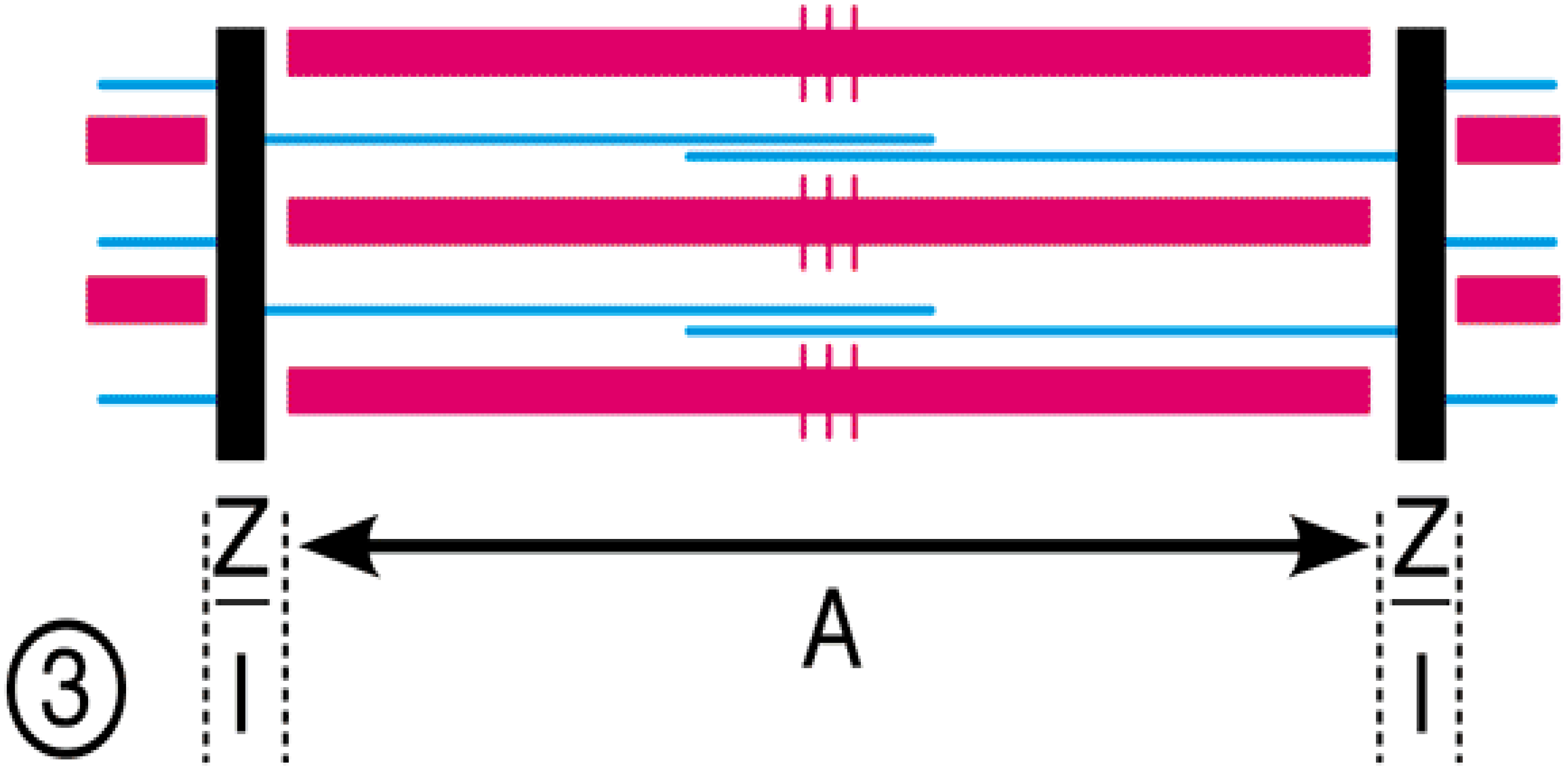
• *FIGURE 10-13* Arrangement of Motor Units Within a Skeletal Muscle. Muscle fibers of different motor units are intermingled, so the net distribution of force applied to the tendon remains constant even when individual muscle groups cycle between contraction and relaxation.

Stimulus

- The stimulus at which the first observable muscle contraction osccurs = Threshold stimulus
- The strongest stimulus represents the point at which all the muscle’s motor units are recruited = Maximal stimulus (increased stimulus does not produce stronger contraction.


Tension
Stimuli
Time

Maximally Contracted



Treppe

- A staircase pattern results from contractions which are initially not as strong as later contractions in response to stimuli of the same strength
- Due to increasing availability of **Ca^{2+}**

Treppe

- Furthermore, as the muscle begins to work & liberate heat, its enzyme systems become more efficient.

- This is the basis for the warm-up period required of athletes.

LENGTH-TENSION RELATIONSHIP

Tension

- The amount of tension produced by an individual muscle fiber depends solely on the number of cross-bridge interactions.
- This is a **all-or-none** response due to the presence of **Ca^{2+}** “on” or absence of **Ca^{2+}** “off” = resting

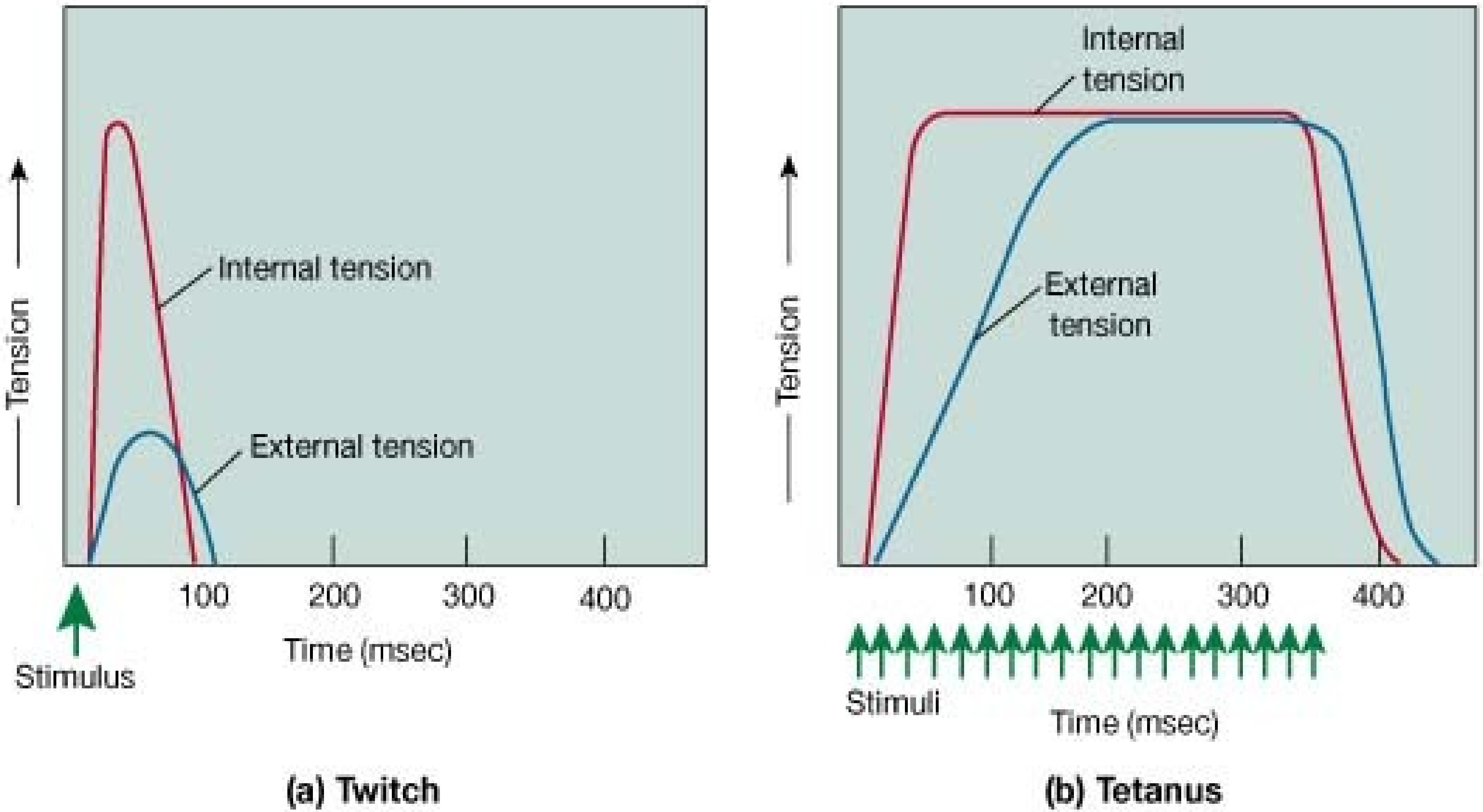


FIGURE 10-12 **Internal and External Tension.** Internal tension rises as the muscle fiber contracts. External tension rises more slowly as the series elastic elements are stretched. **(a)** During a single twitch contraction, external tension cannot rise as high as internal tension before the relaxation phase begins. **(b)** During a tetanic contraction, external tension soon plateaus at a level that is roughly equivalent to internal tension. External tension remains elevated for the duration of the contraction.

Isotonic Contractions

- The muscles changes in length (decreasing the angle at the joint) and moves the load.
- Once the resistance is overcome, tension remains constant for the rest of the contraction & muscle shortens.

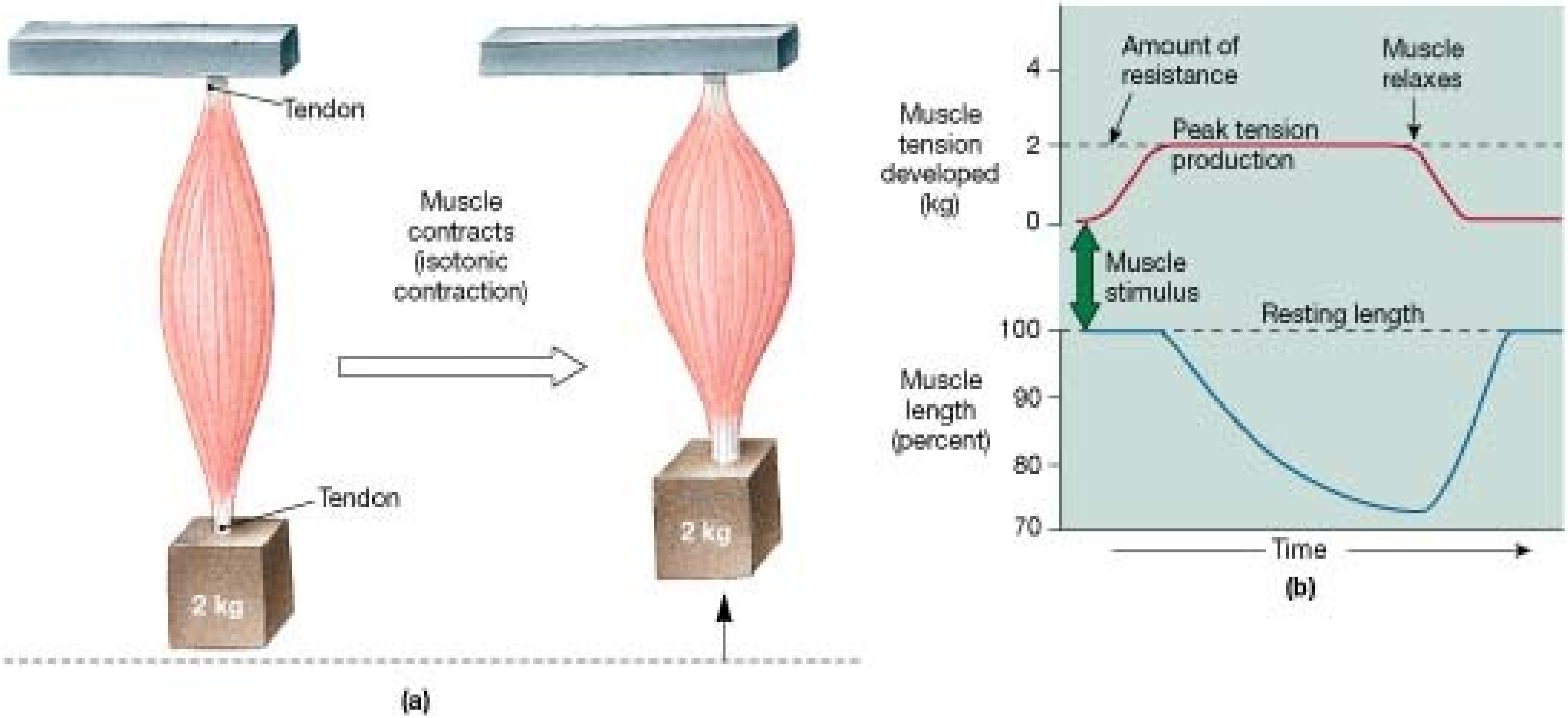
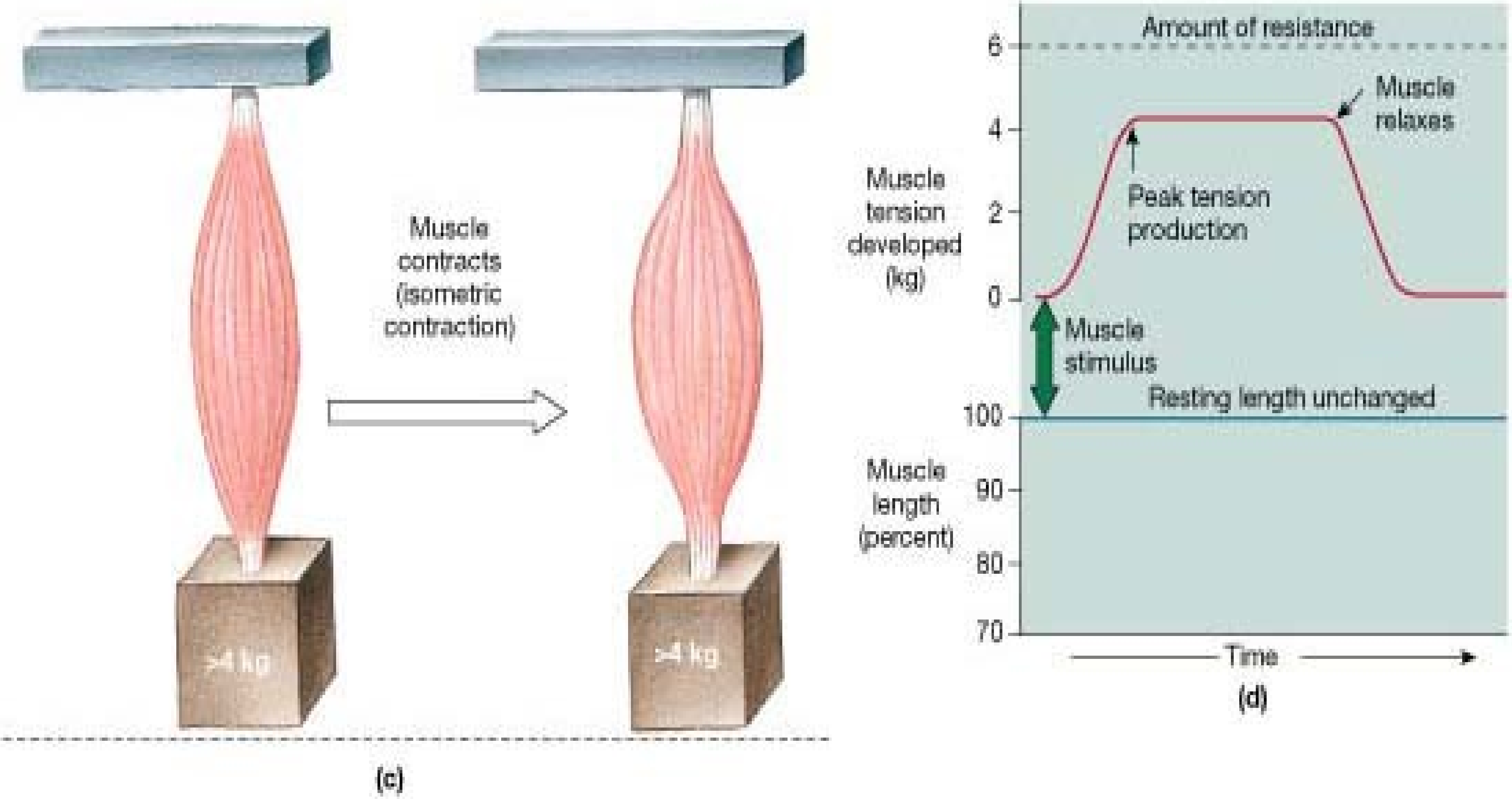


FIGURE 10-14 **Isotonic and Isometric Contractions.** **(a,b)** This muscle is attached to a weight less than its peak tension capabilities. On stimulation, it develops enough tension to lift the weight. Tension remains constant for the duration of the contraction, although the length of the muscle changes. This is an example of isotonic contraction.

Isometric Contractions

- When stimulated, the tension increases to the muscle’s peak tension-developing capability, but the muscle <u>does not shorten.</u>
- Muscles that act primarily to maintain upright posture or to hold joints in stationary positions



•*FIGURE 10-14* **Isotonic and Isometric Contractions. (c,d)** The same muscle is attached to a weight that exceeds its peak tension capabilities. On stimulation, tension will rise to a peak, but the muscle as a whole cannot shorten. This is an isometric contraction.

MUSCULAR PERFORMANCE & ENDURANCE

Endurance

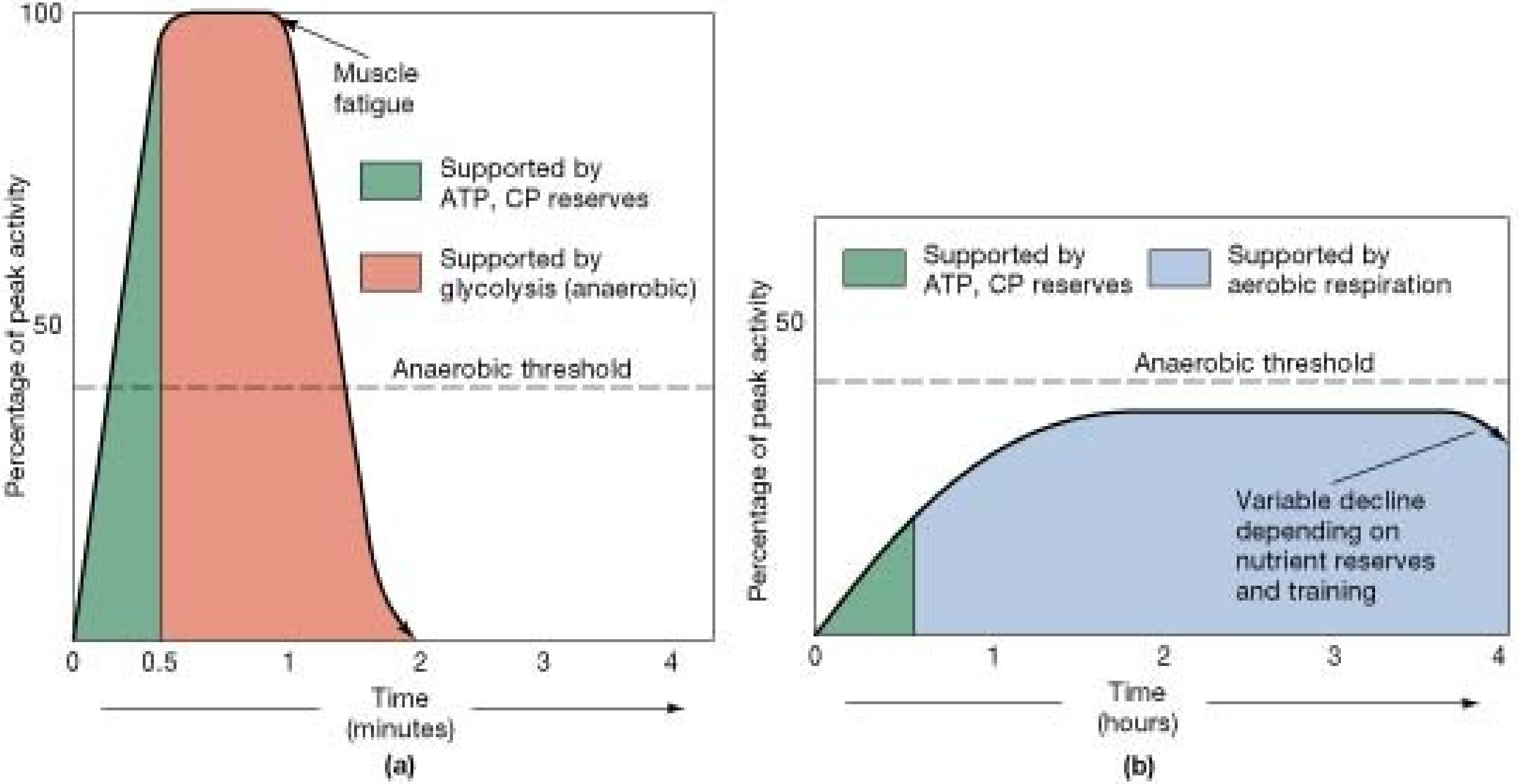
- As muscle contracts, **ATP** provides the energy for cross bridge movement & detachment & and Ca^{2+} pump.
- Limited reserves of **ATP** ->4 to 6 seconds.
- Creatine Phosphate - stored in muscles is used to regenerate ATP -> 15 seconds

Aerobic Endurance

- Aerobic exercise requires an adequate supply:
  - **Glucose** & **O_2**
- Energy sources are - free fatty acids for adipose tissue and amino acids from protein catabolism
- ATP's - 36 per glucose
- Duration -> hours

Anaerobic Endurance

- Glycolysis
- Lactic acid formed and release into blood stream
- Energy source - Glucose
- No oxygen usage
- ATP’s - **2** per glucose
- Duration ->30 to 60 seconds



• ***FIGURE 10-18*** **Muscular Performance and Endurance.** **(a)** At peak levels of activity, skeletal muscles rely primarily on glycolysis for ATP production, with associated lactic acid production. Initial burst activity is supported by ATP and CP reserves. Muscles operating at peak levels fatigue rapidly. **(b)** Muscular activity can continue for extended periods when ATP demands are kept below the anaerobic threshold.

Muscle Fatigue

- A situation in which the muscle is unable to contract and its tension drops to zero

- A key factor in muscle fatigue is the muscle’s inability to produce enough **ATP** to power contraction.

Factors Influencing Force, Velocity, & Duration of Skeletal Contraction

Muscle Size

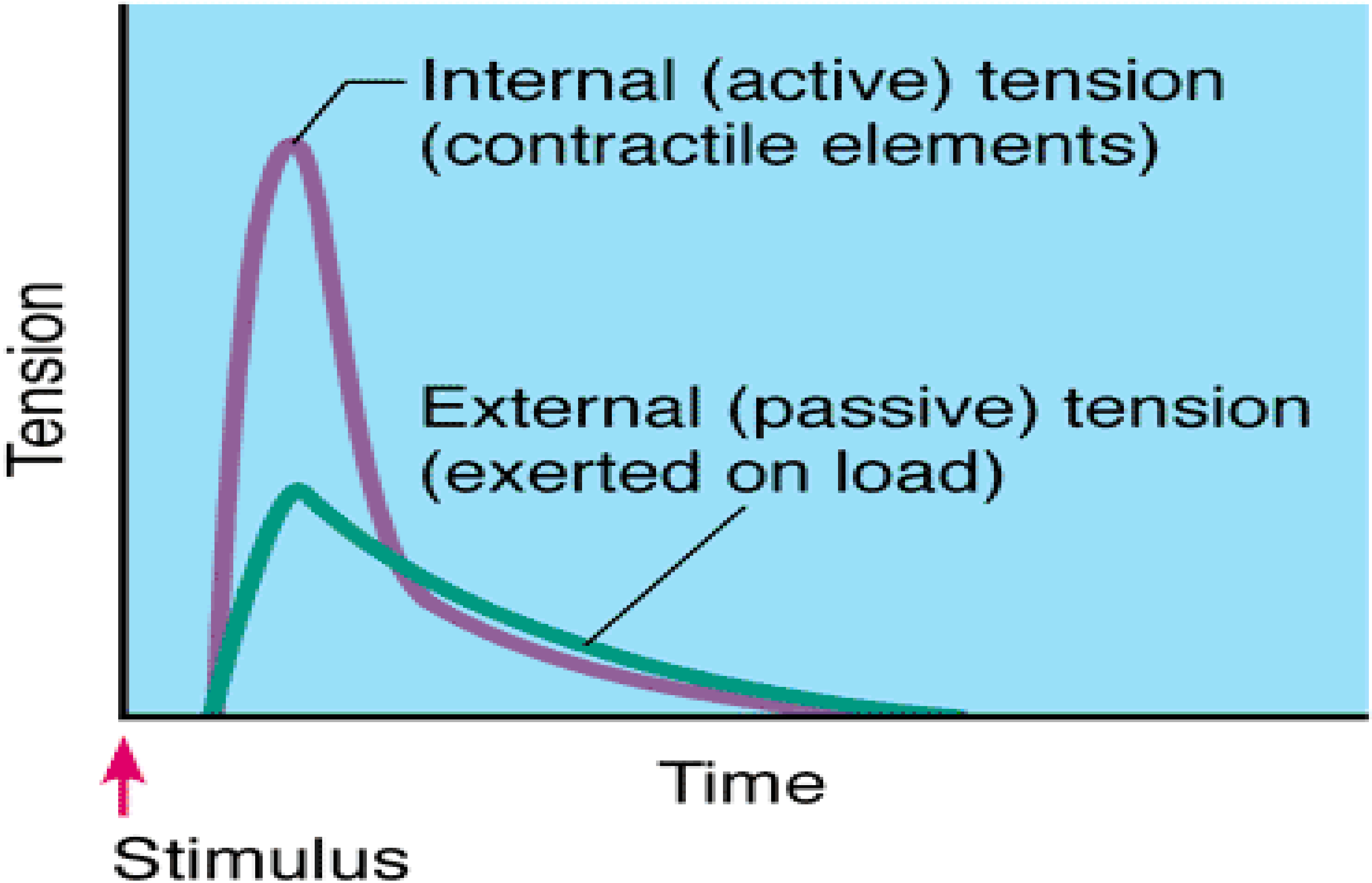
- The greater the cross-sectional area, the more tension it can develop & the greater its strength.
- Regular exercise increase muscle force by causing muscles cells to *hypertrophy*, in crease in size by adding new myofibrils.

Series-Elastic Elements

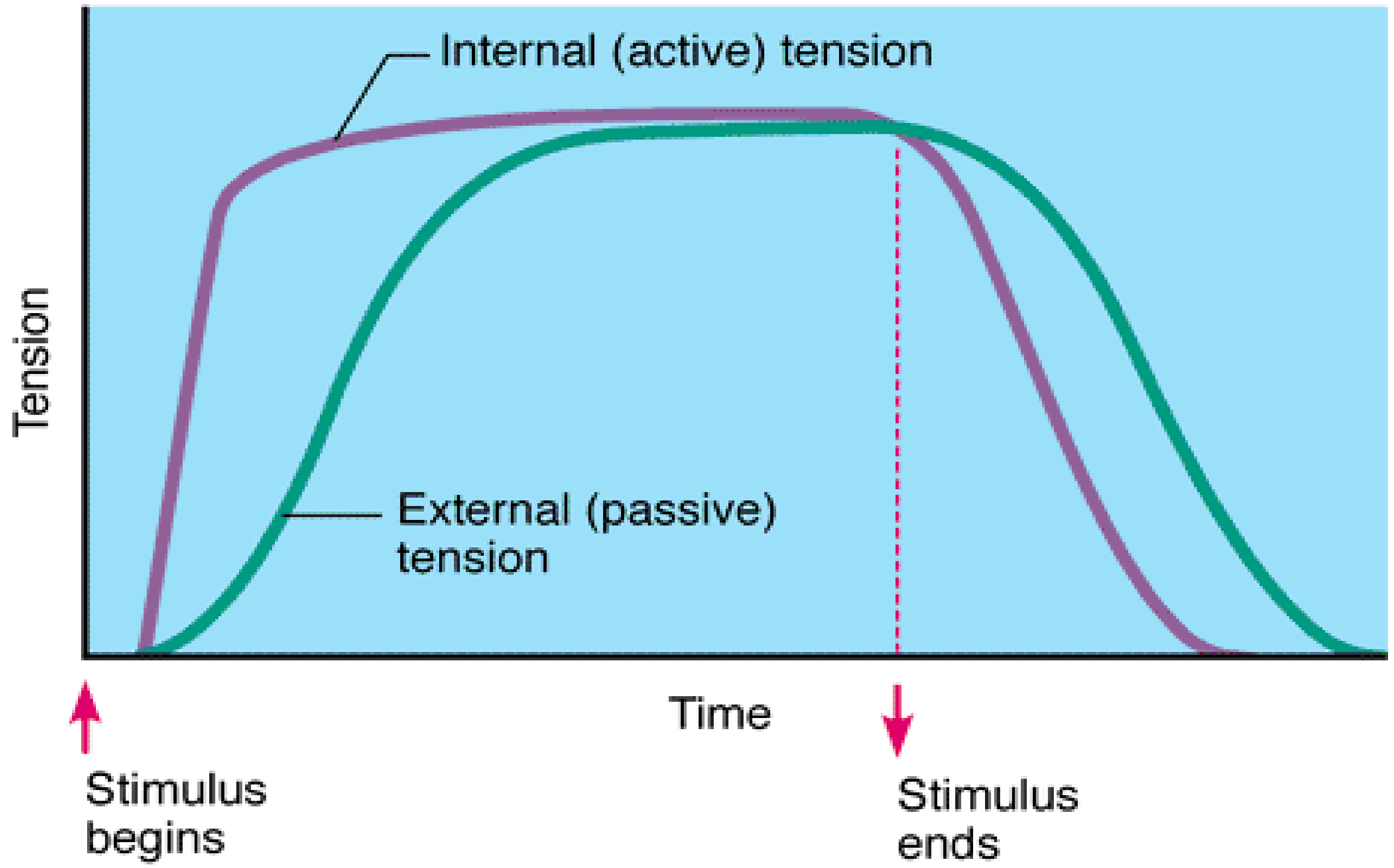
- All of the noncontractile structures of muscles are collectively called - series-elastic elements because they are able to stretch and recoil.

Internal & External Tension

- The force produces internal tension - generated by the contractile elements - myofibrils, which stretches the series-elastic elements
- These in turn transfer their tension, called external tension, to the load.


Internal (active) tension
(contractile elements)
External (passive) tension
(exerted on load)
Tension
Time
Stimulus

(a) Twitch



(b) Tetanic contraction

Degree of Muscle Stretch

- The ideal length-tension relationship within a sarcomere occurs when a muscle is slightly stretched & the actin & myosin filaments barely overlap.
- This allows sliding along nearly the entire length of the actin filaments.

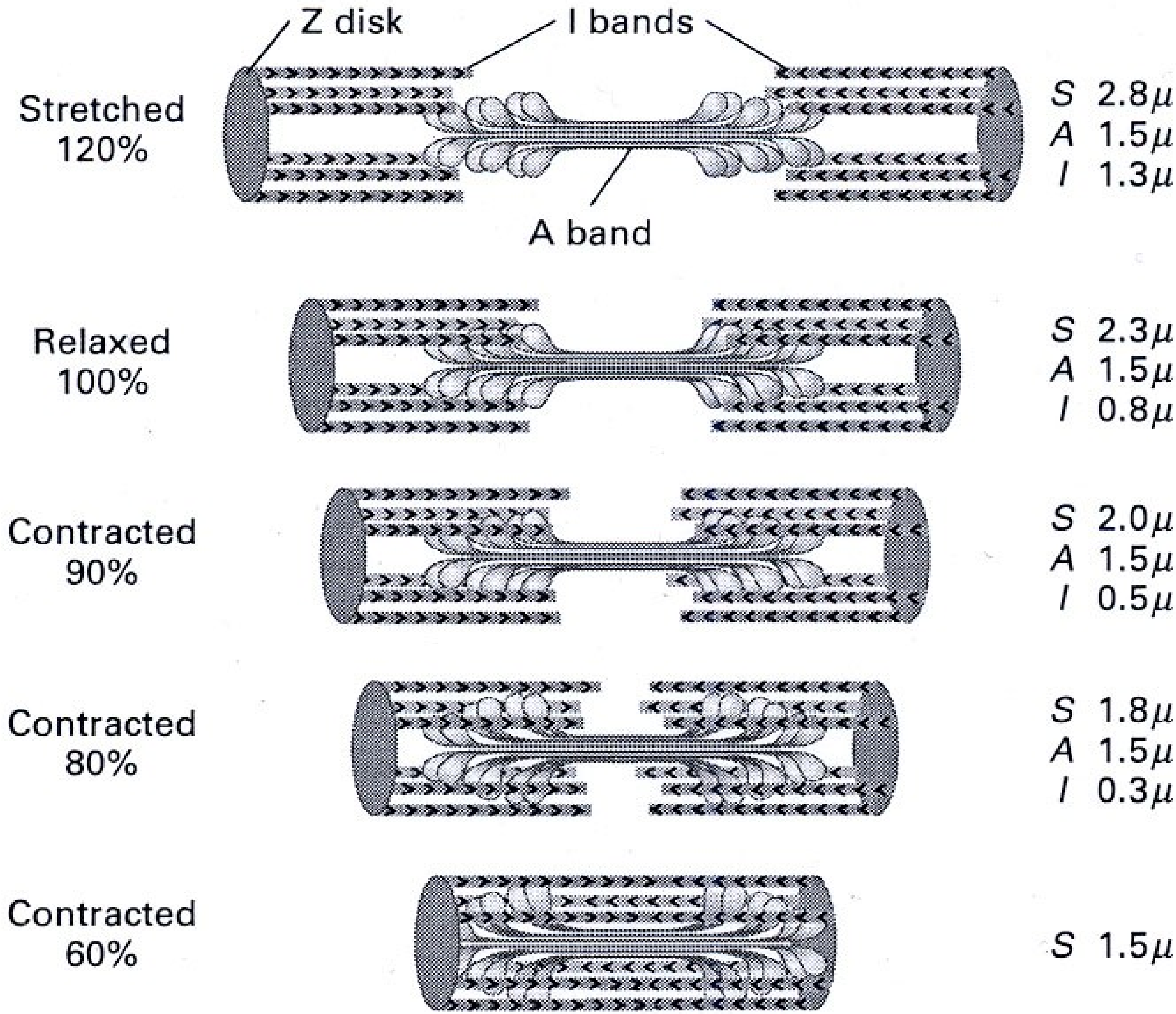
Degree of Muscle Stretch

- If stretched to far the myofilaments do not overlap and no contraction can occur.
- If the sarcomere are so compressed & cramped, little or no further shortening can occur.

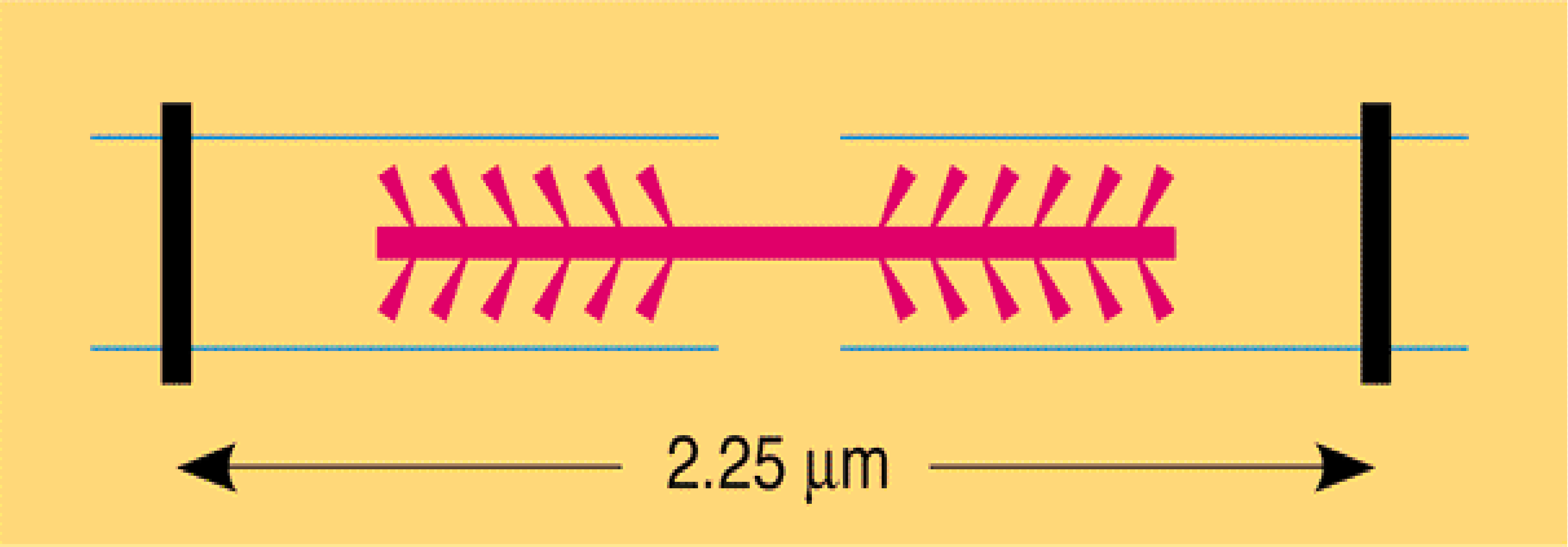
Degree of Muscle Stretch

- Maximum force generation is possible when the muscle is a little over 100% of its resting length.

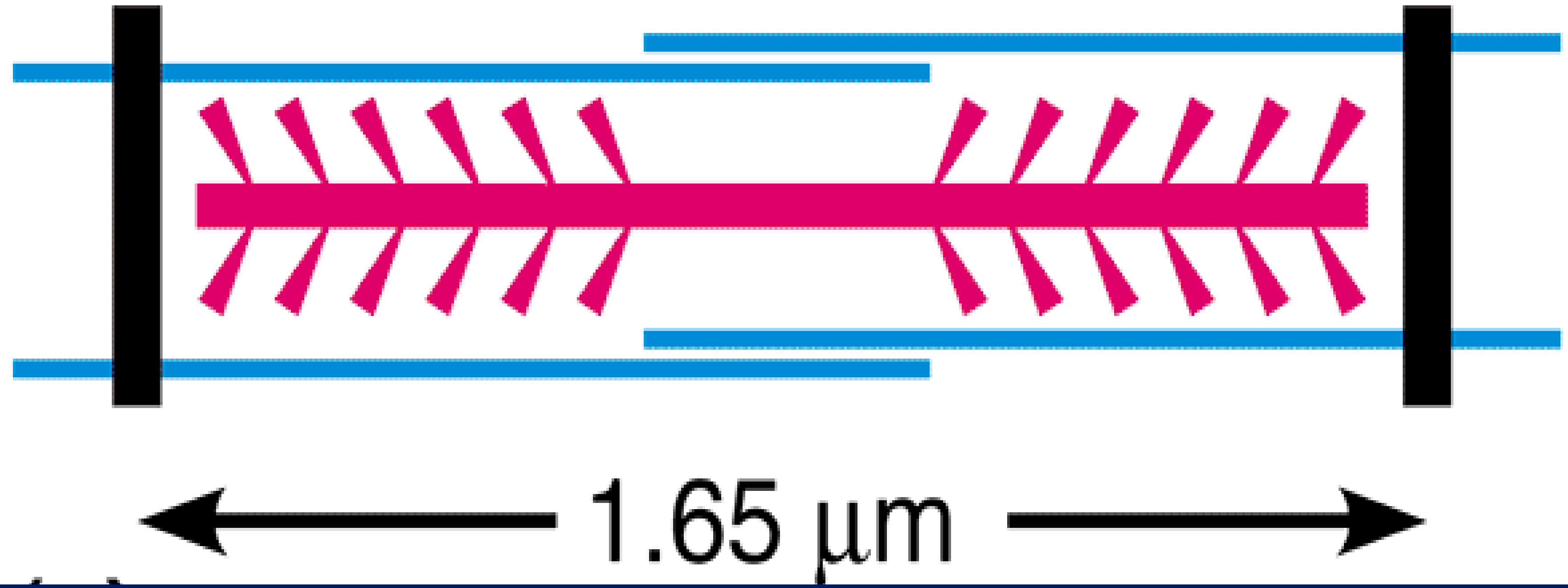
▲ **FIGURE 18.1 Schematic diagram of muscle contraction and stretch observed by Hanson and Huxley.** The lengths of the sarcomere (S), the A band (A), and the I band (I) were measured from 60 percent contraction (bottom) to 120 percent stretch (top). The lengths of the sacromere, the I band, and A band are noted on the left. Notice that from 120 percent stretch to 70 percent contraction the A band does not change in the length, whereas the length of the I band can stretch to 1.3 microns, then contract to 0.3 microns. At 60 percent contraction, the I band disappears, and the A band shortens to the overall length of the sarcomere. [Adapted from J. Hanson and H. E. Huxley, 1955, *Symp. Soc. Exp. Biol. Fibrous Proteins and their Biological Significance* **9:**249.]


Z disk
I bands
A band
Stretched
120%
S 2.8μ
A 1.5μ
I 1.3μ
Relaxed
100%
S 2.3μ
A 1.5μ
I 0.8μ
Contracted
90%
S 2.0μ
A 1.5μ
I 0.5μ
Contracted
80%
S 1.8μ
A 1.5μ
I 0.3μ
Contracted
60%
S 1.5μ

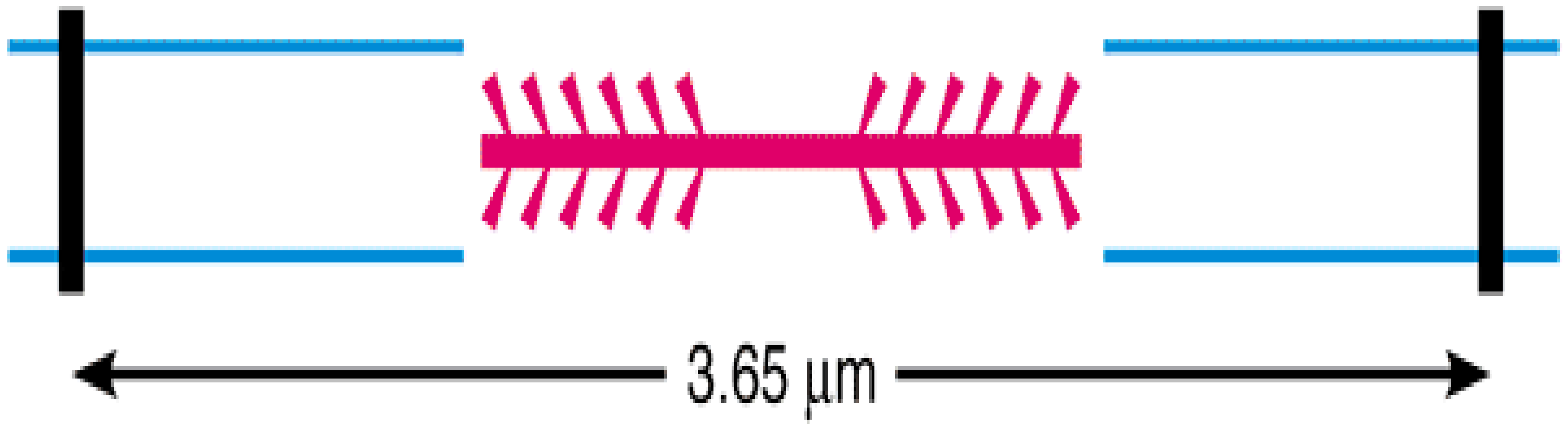
At Normal Resting Length = 100%



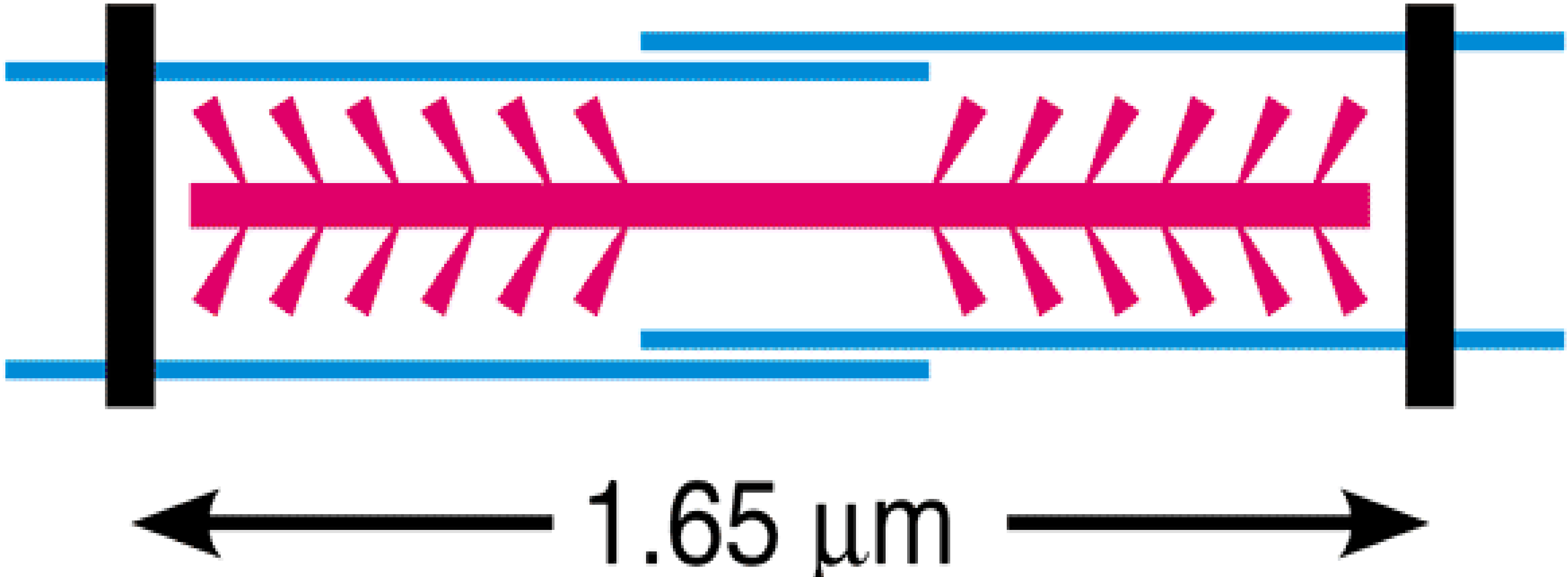
Strong Contraction ~ 75% of Resting Length

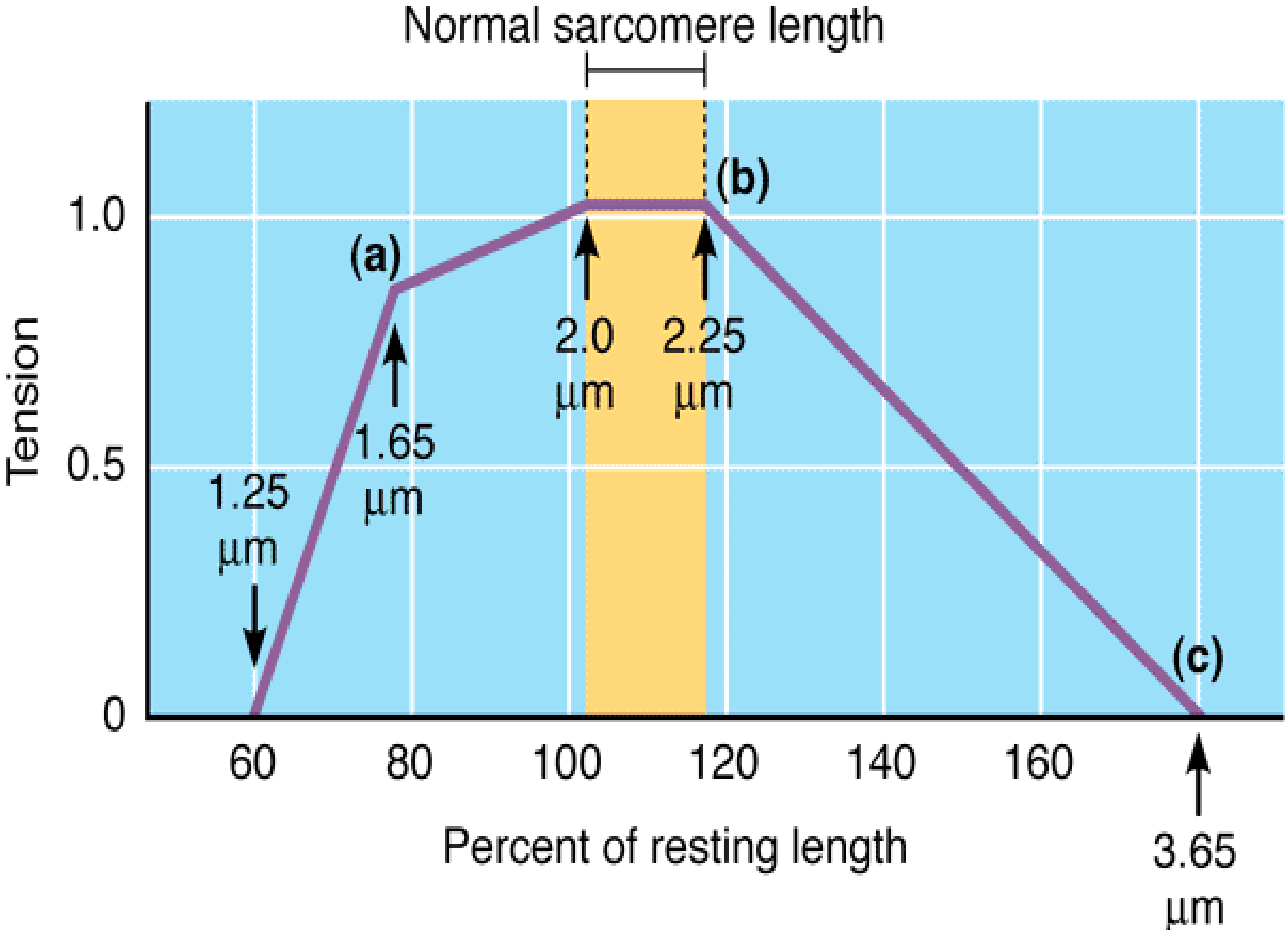


Excessively Stretched ~170% of Resting Length



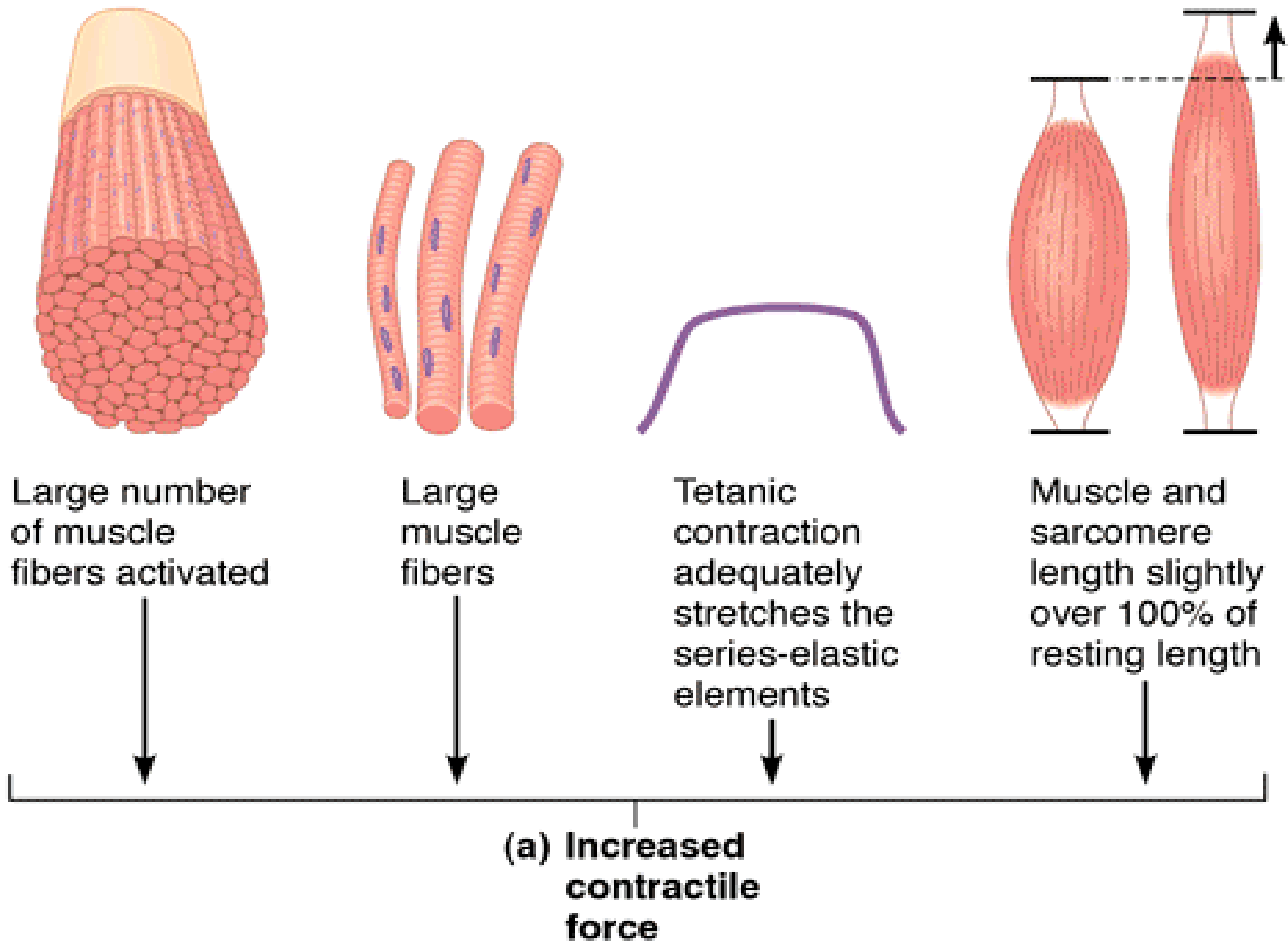
Maximal Compression = Z discs abut myofilaments




Normal sarcomere length
Tension
1.0
0.5
0
(a)
(b)
(c)
1.25 µm
1.65 µm
2.0 µm
2.25 µm
3.65 µm
60
80
100
120
140
160
Percent of resting length

Force of Contraction

- Number of muscle fibers contracting
- The relative size of the muscle
- Series-elastic elements
- The degree of muscle stretch


Large number of muscle fibers activated
Large muscle fibers
Tetanic contraction adequately stretches the series-elastic elements
Muscle and sarcomere length slightly over 100% of resting length
(a) Increased contractile force

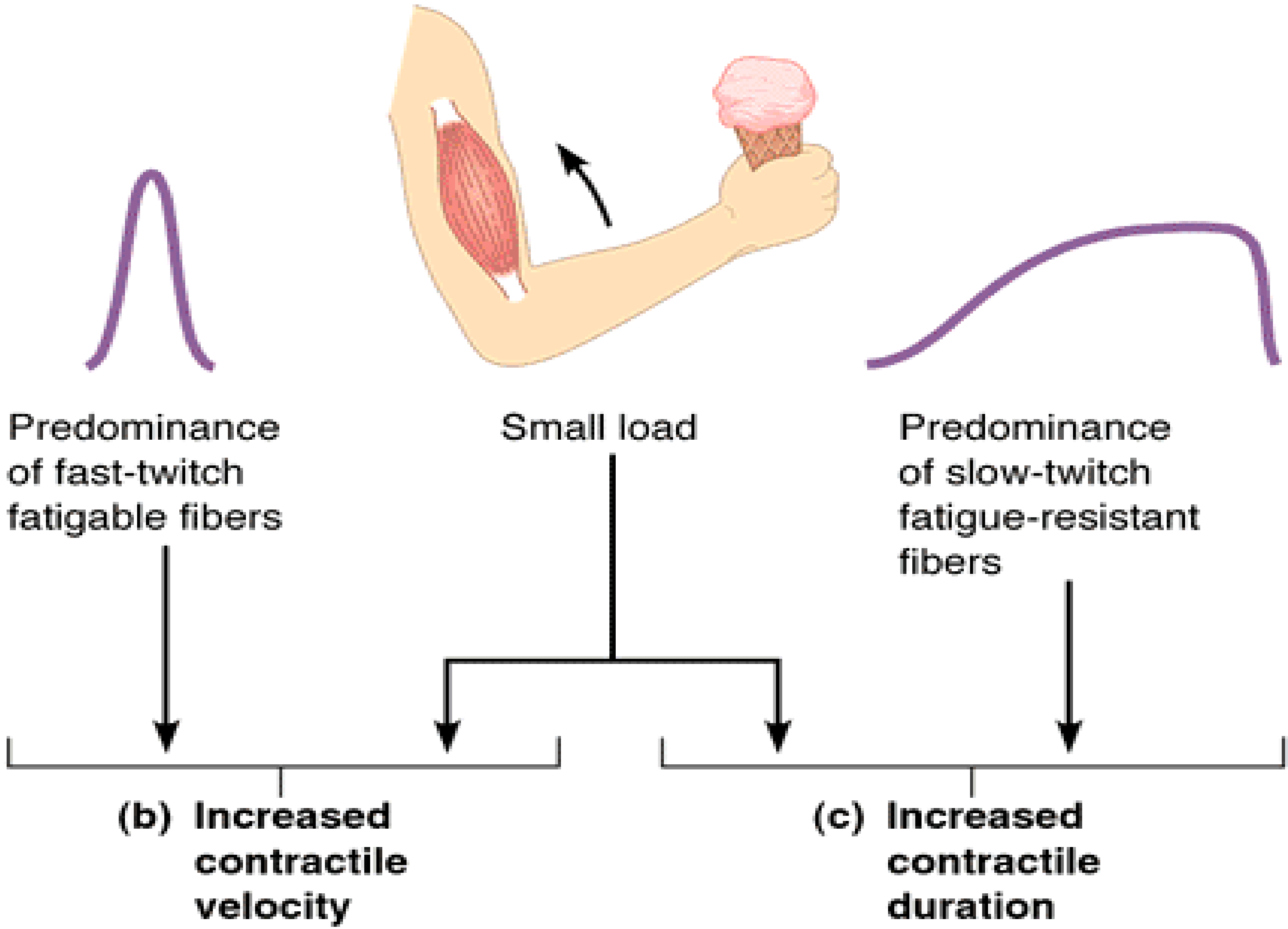
Slow & Fast Fibers

Muscle Fiber Types

- One component of the myosin molecules, the heavy chain, determines the functional characteristics of the muscle fiber.
- Three different varieties, designated type I (slow fibers) and type II*a* & IIx (fast fibers)

Muscle Fiber Types

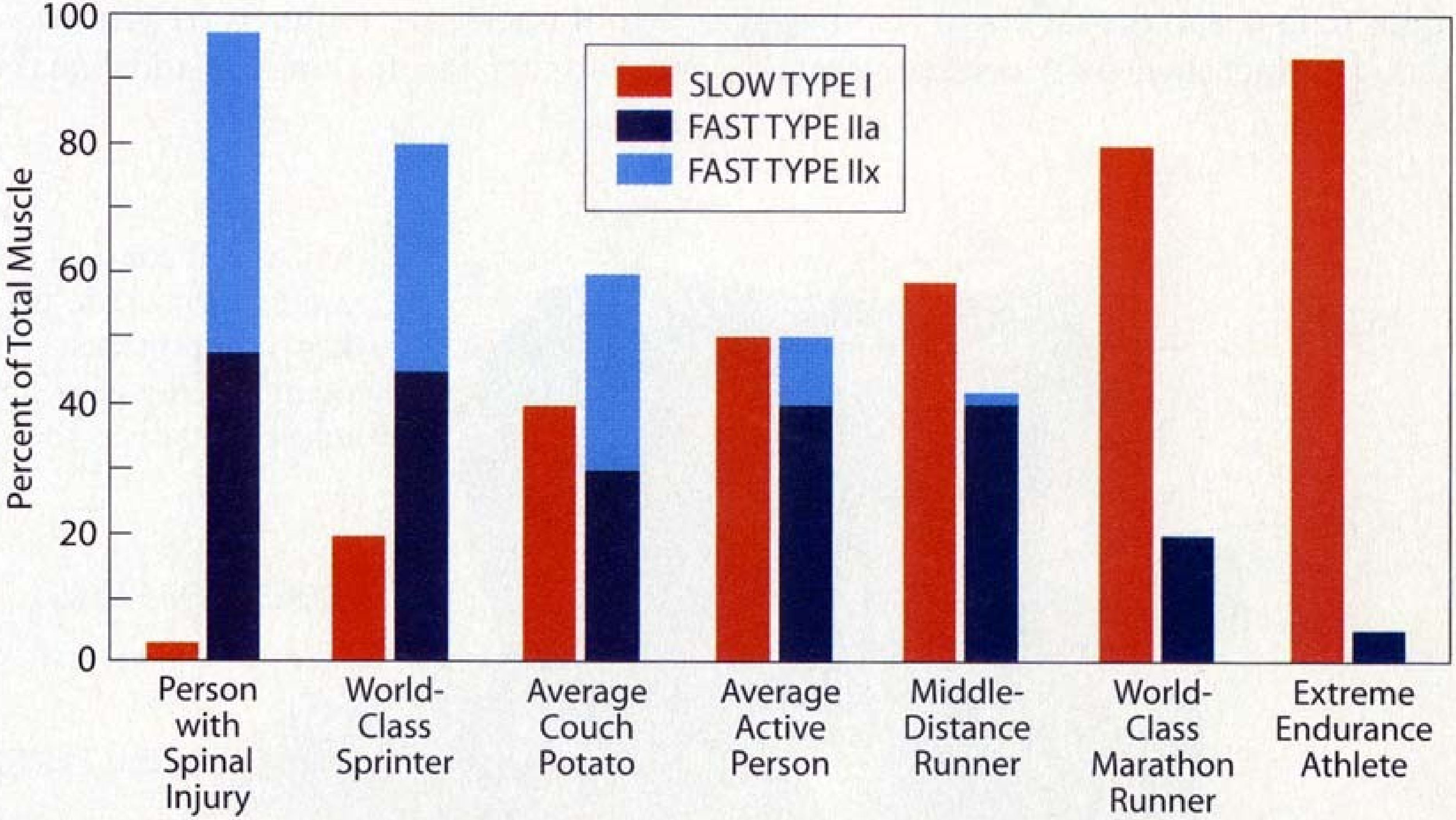
- The maximum contractile velocity of a type I or slow fiber is about one tenth that of IIx (fast fibers).
- The velocity of a type IIa fibers is somewhere between those of type I and Iix.


Predominance of fast-twitch fatigable fibers
Small load
Predominance of slow-twitch fatigue-resistant fibers
(b) Increased contractile velocity
(c) Increased contractile duration

Muscle, Genes and Athletic Performance

The cellular biology of muscle helps to explain why a particular athlete wins and suggests what future athletes might do to better their odds

by Jesper L. Andersen, Peter Schjerling and Bengt Saltin

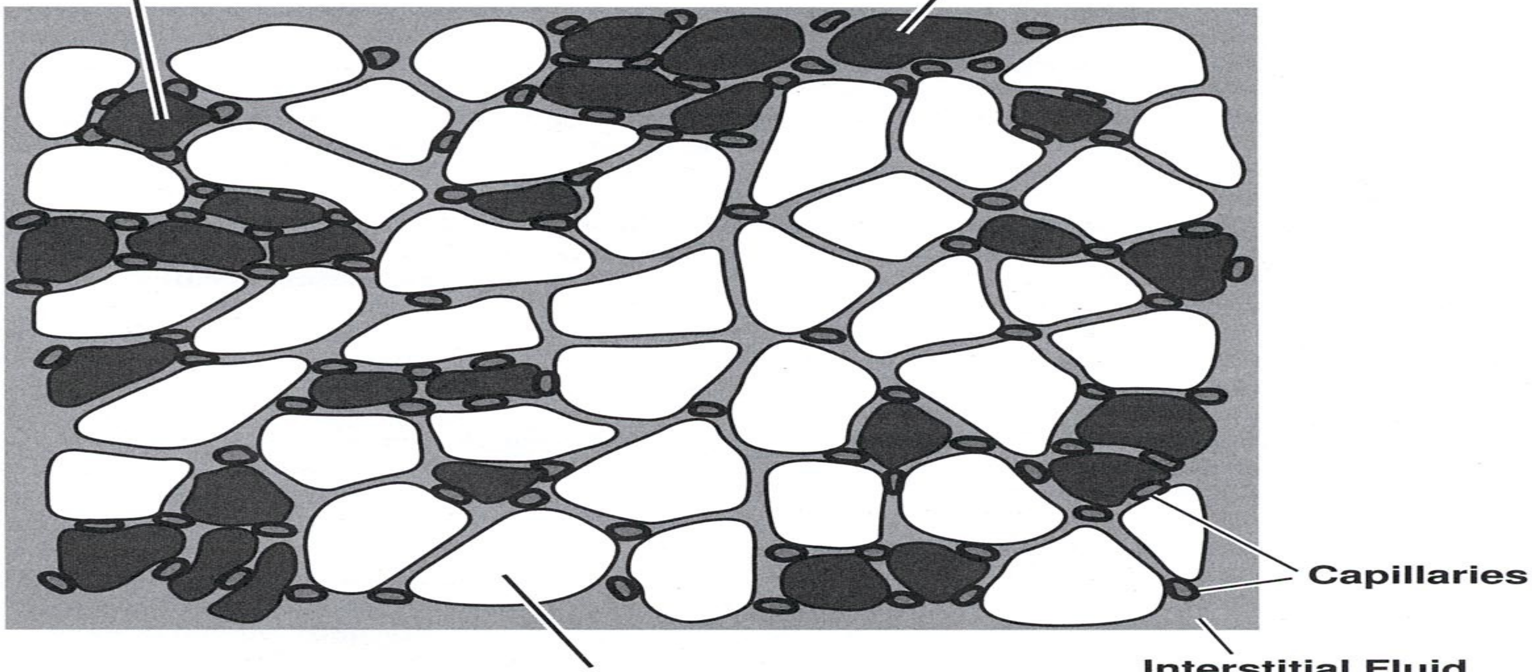


WORLD-CLASS SPRINTER BRIAN LEWIS of the U.S. (*opposite page*) has a larger proportion of so-called fast muscle fibers in his legs than a marathoner or an extreme endurance athlete does. Fast IIx fiber contracts 10 times faster than slow type I fiber, and type IIa lies somewhere in between.

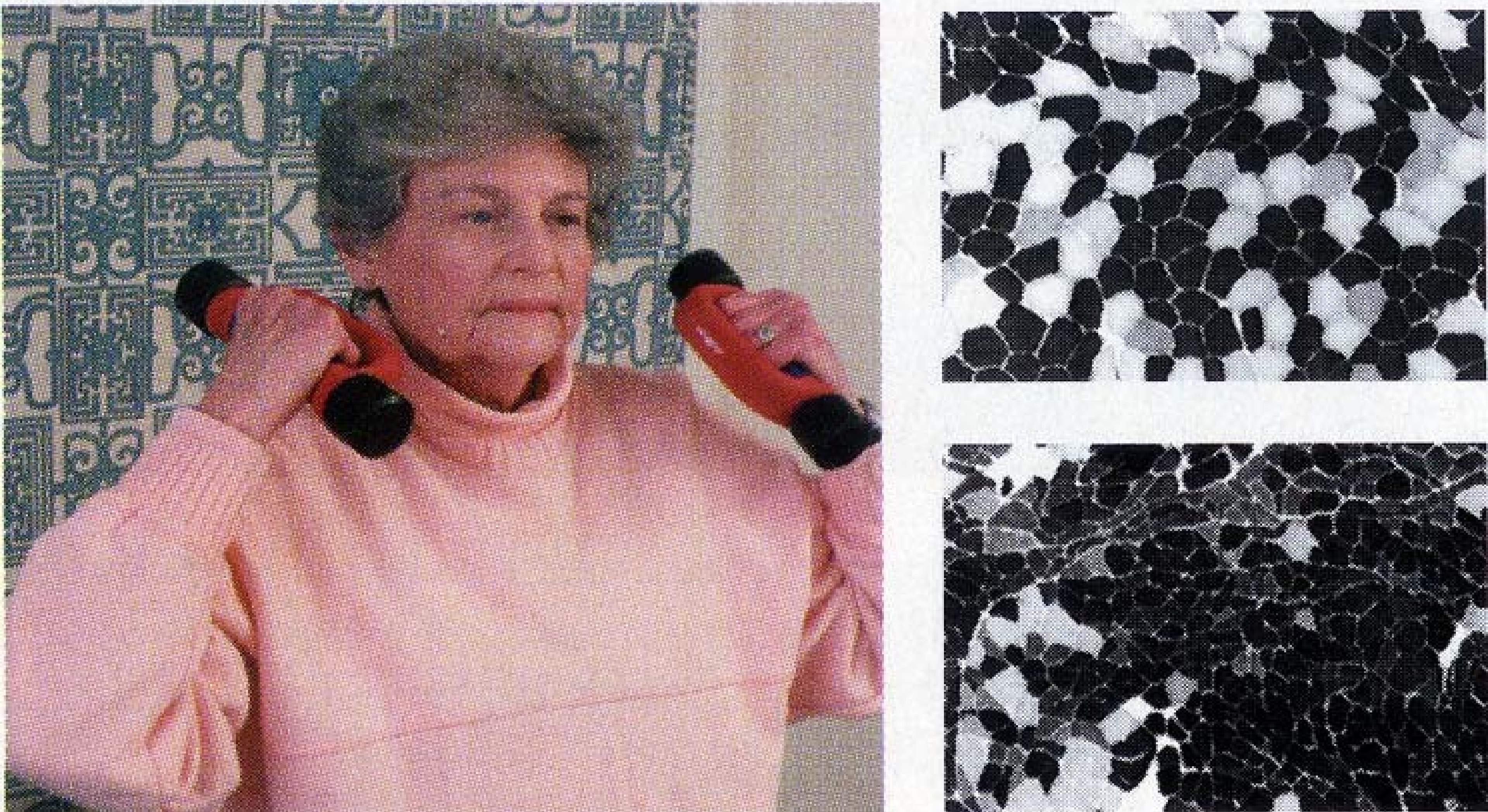
SKELETAL MUSCLE FIBER TYPES
Cross Section

Slow Oxidative Fibers
ATP Production : oxidative phosphorylation
Contraction Speed : slow
ATPase Activity : slow
Myoglobin Concentration : high
Mitochondria : many
Capillaries : many
Endurance : high
Diameter : small
Fiber color : red

Fast Oxidative Fibers
ATP Production : oxidative phosphorylation
Contraction Speed : fast
ATPase Activity : fast
Myoglobin Concentration : high
Mitochondria : many
Capillaries : many
Endurance : intermediate
Diameter : intermediate
Fiber color : red



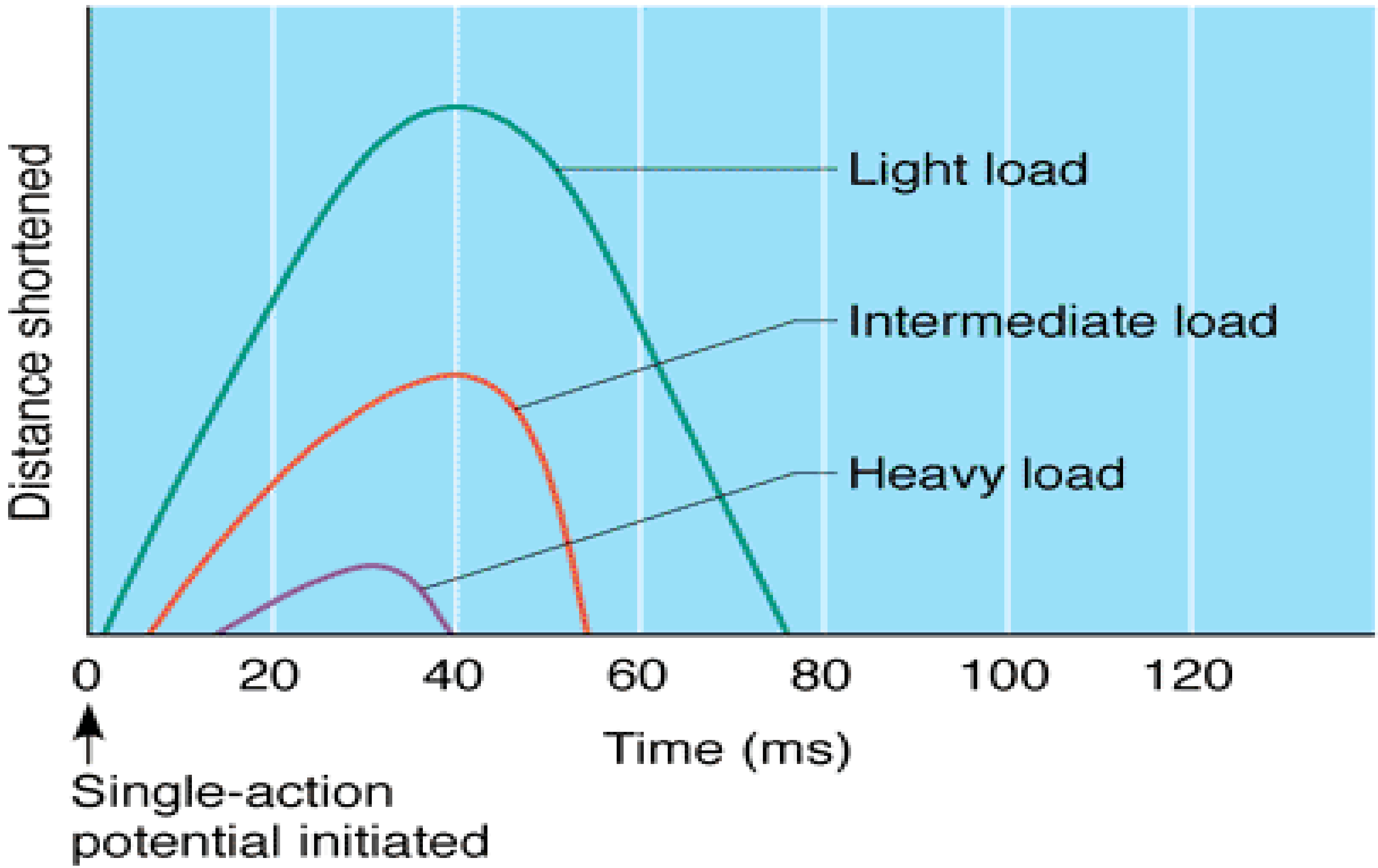
Fast Glycolytic Fibers
ATP Production : anaerobic glycolysis
Contraction Speed : fast
ATPase Activity : fast
Myoglobin Concentration : low
Mitochondria : few
Capillaries : few
Endurance : low
Diameter : large
Fiber color : white

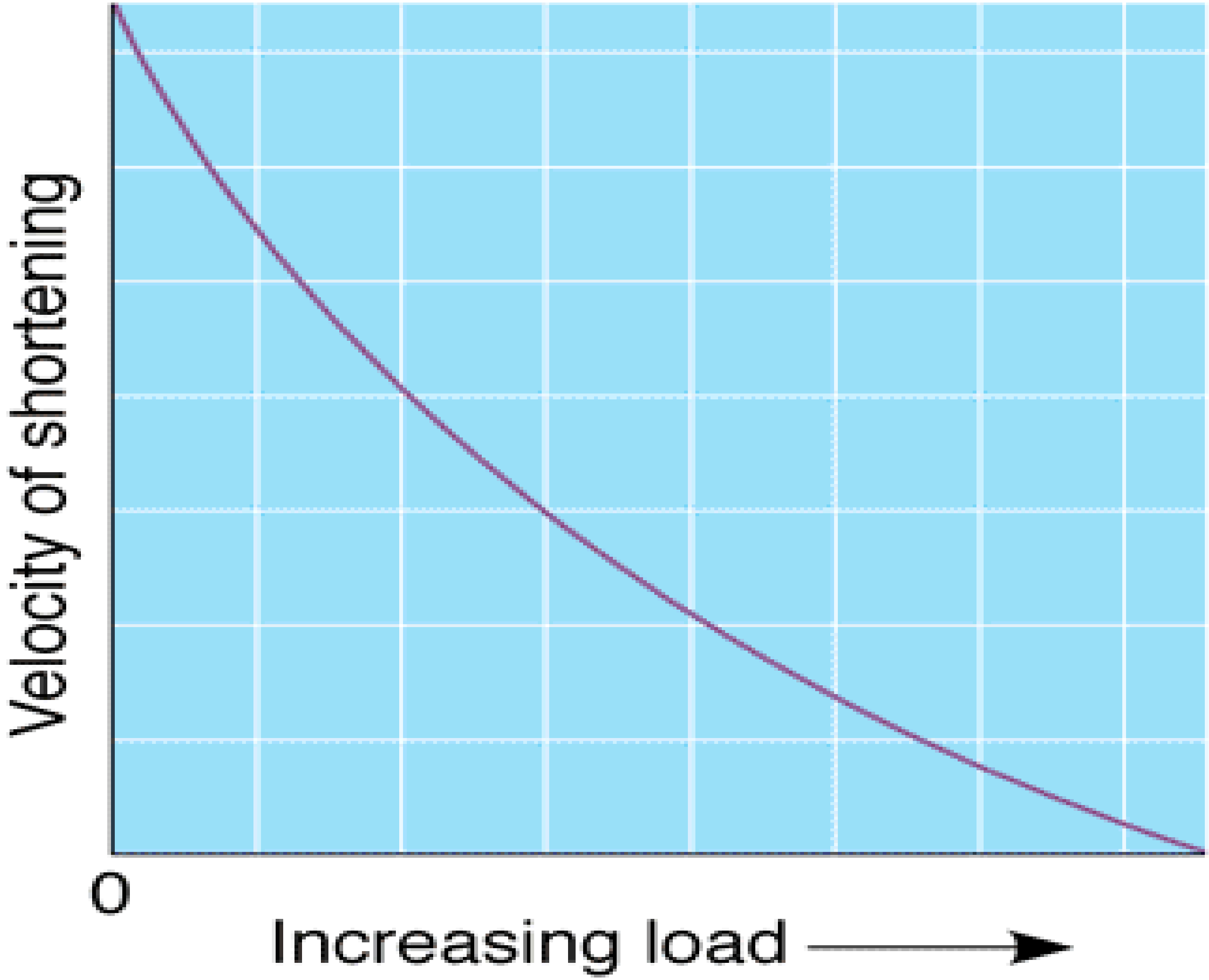


WEIGHT LIFTING can prevent some loss of muscle mass. But nothing can prevent changes in the shape and distribution of different types of muscle fiber as we age (young muscle, *top;* elderly muscle, *bottom*).

Resistance & Speed of Contraction

- There is an inverse correlation between the amount of resistance & the speed of contraction
- That is, you can lift a light object more quickly than a heavy object.


Distance shortened
Light load
Intermediate load
Heavy load
0
20
40
60
80
100
120
Time (ms)
Single-action
potential initiated
(a)



(b)

Muscle Tone

- Muscles in a relaxed state are in a slightly contracted state = Muscle Tone
- This is due to spinal reflexes responding to stretch receptors in muscles & tendons
- Muscle tone keeps muscles firm, healthy, & ready to respond.

Smooth Muscle

KEY POINTS

- **3) Smooth Muscle**
  - *Location : walls* of hollow organs; blood vessels; iris and ciliary muscles; arrector pili (hair).
  - *Microscopic Appearance* : no striations; single nucleus; spindle-shaped fibers.
  - *Fiber Diameter : 3* to 8 micrometers.
  - *Fiber Length : 30* micrometers to 200 micrometers.

KEY POINTS

- **3) Smooth Muscle**
  - *Nervous Control : involuntary* (unconscious) control by the autonomic nervous system.
  - *Regeneration : more* than other muscle tissues; much less than epithelial tissues.
  - *Functions* mixes and propels luminal contents through the digestive tract; regulates the flow of blood through blood vessels; pili muscles causes hairs to stand up (goose pimples); etc.

SMOOTH MUSCLE

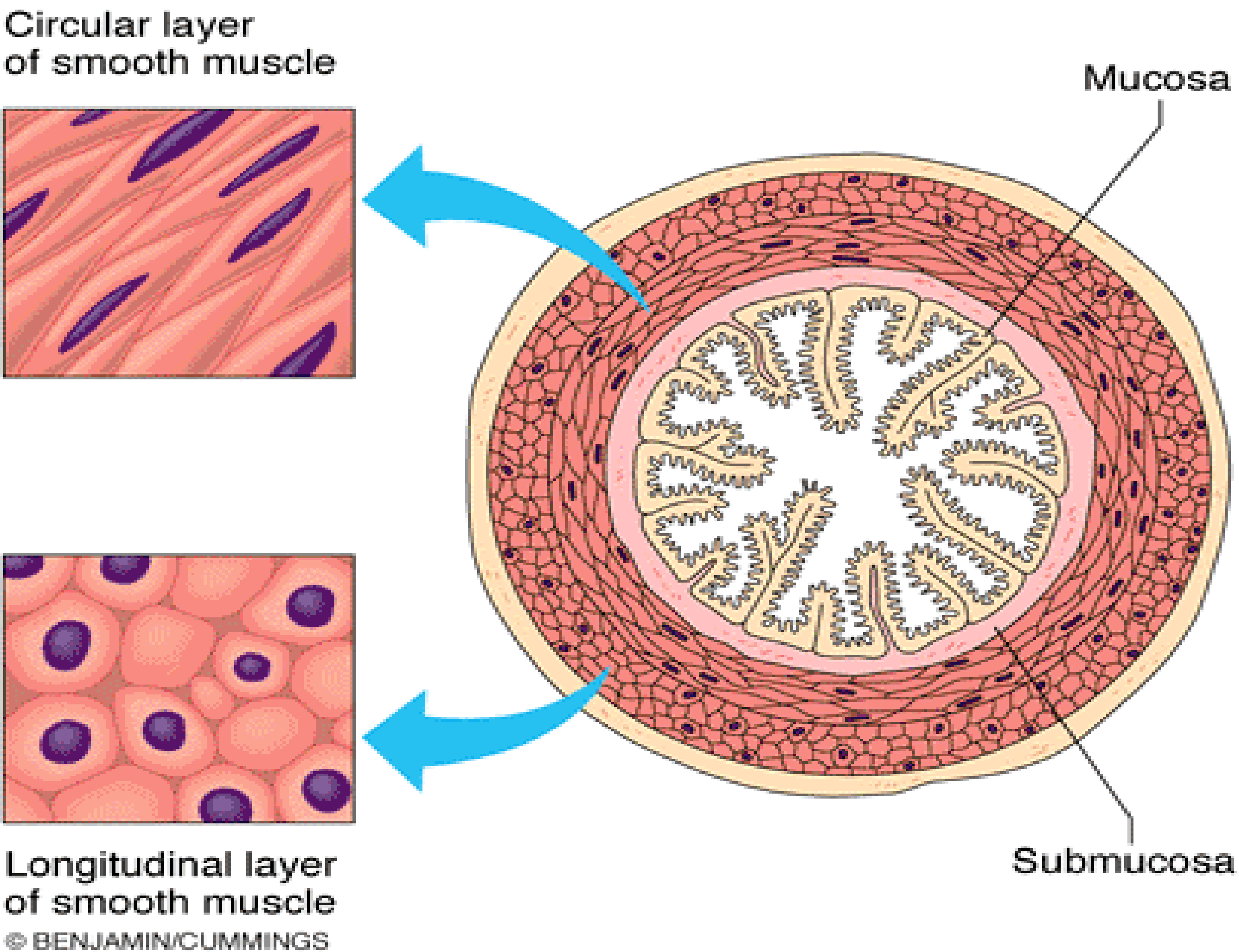
- Spindle-shaped cells - Fusiform in shape
- 2-10 um wide & 100s um long
- Lack coarser connective tissues sheaths seen in skeletal muscle, but have a small amount of endomysium
- Most are organized into sheets of closely apposed fibers

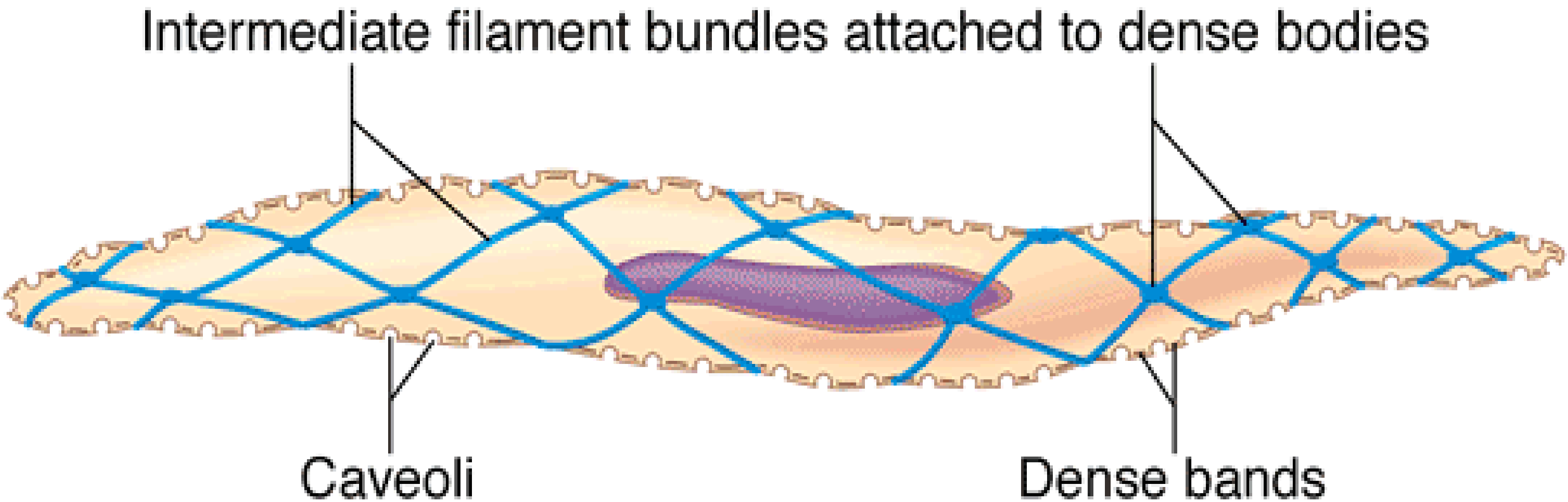
SMOOTH MUSCLE

- Found in walls of hollow organs & blood vessels
- Under autonomic control
  - Maintain “tone”
- Not striated (no sarcomeres)
  - Do contain actin & myosin
    - Attached to dense bodies
- Calmodulin-Ca^{++} complex allows for cross bride binding on myosin heads

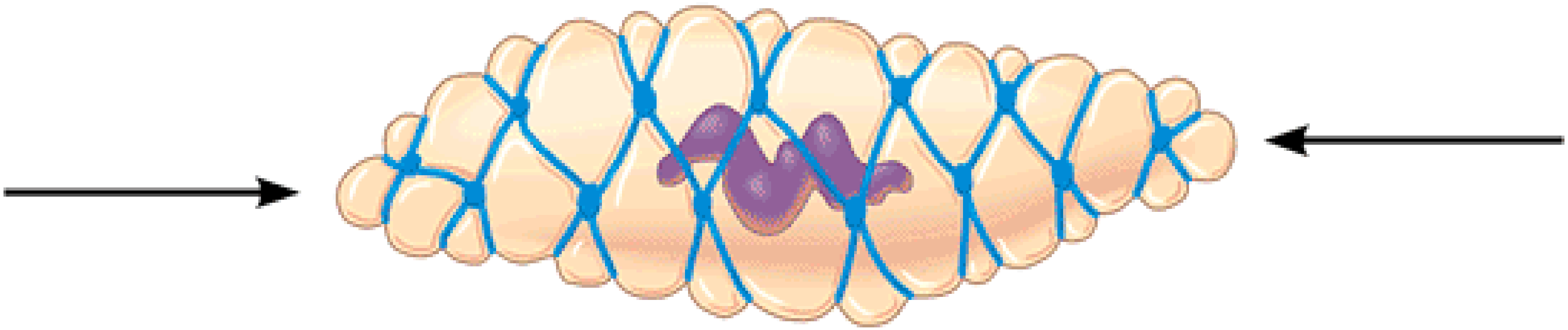
SMOOTH MUSCLE

- No striations
- No sarcomeres
- No troponin complex
- Due have thick & thin filaments
- Contract in a corkscrew-like fashion

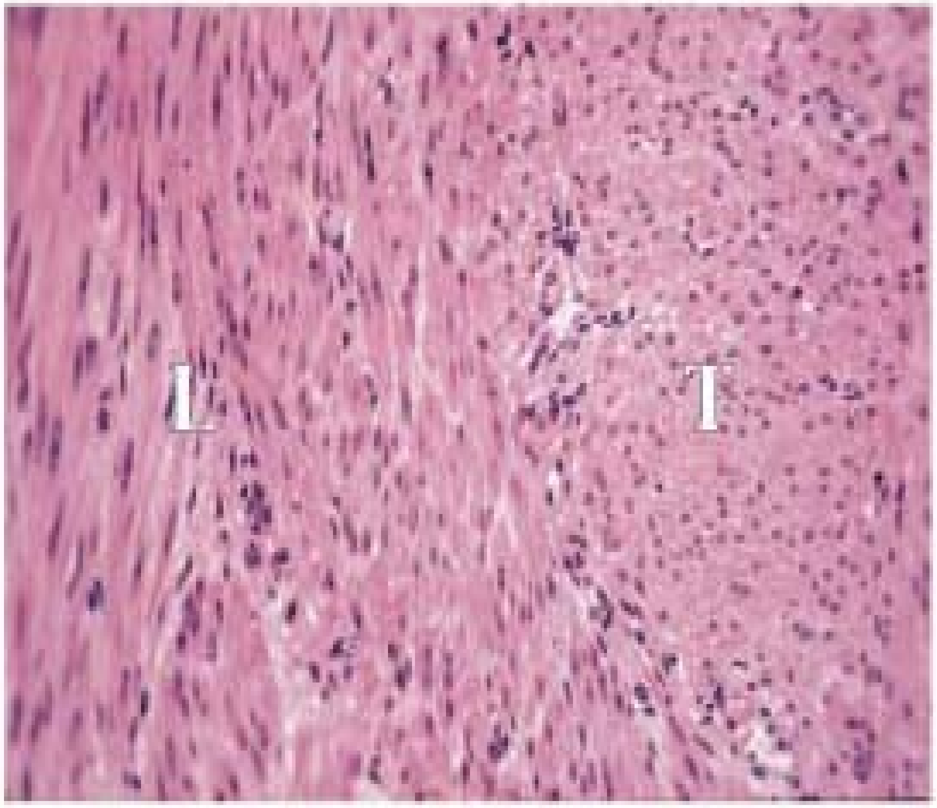

Circular layer
of smooth muscle
Mucosa
Submucosa
Longitudinal layer
of smooth muscle
© BENJAMIN/CUMMINGS



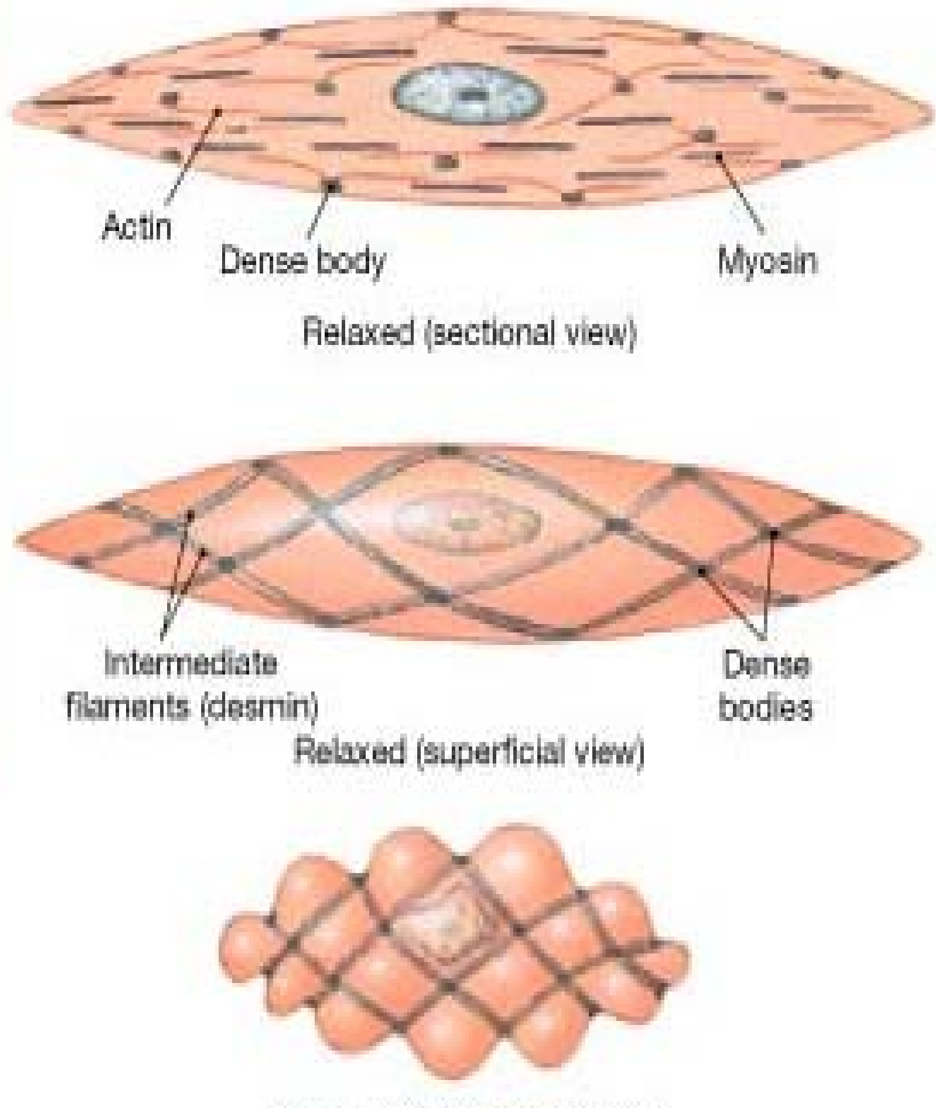
(a) Relaxed smooth muscle cell



(b) Contracted smooth muscle cell

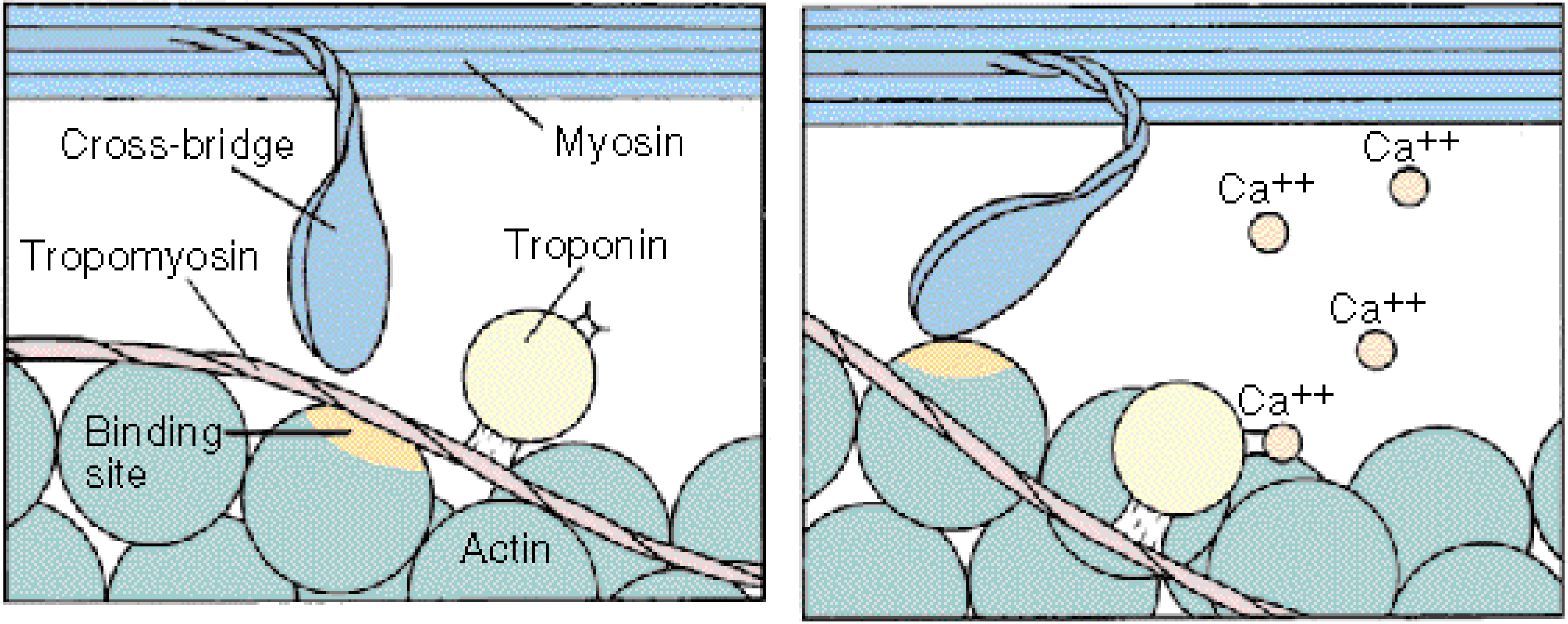


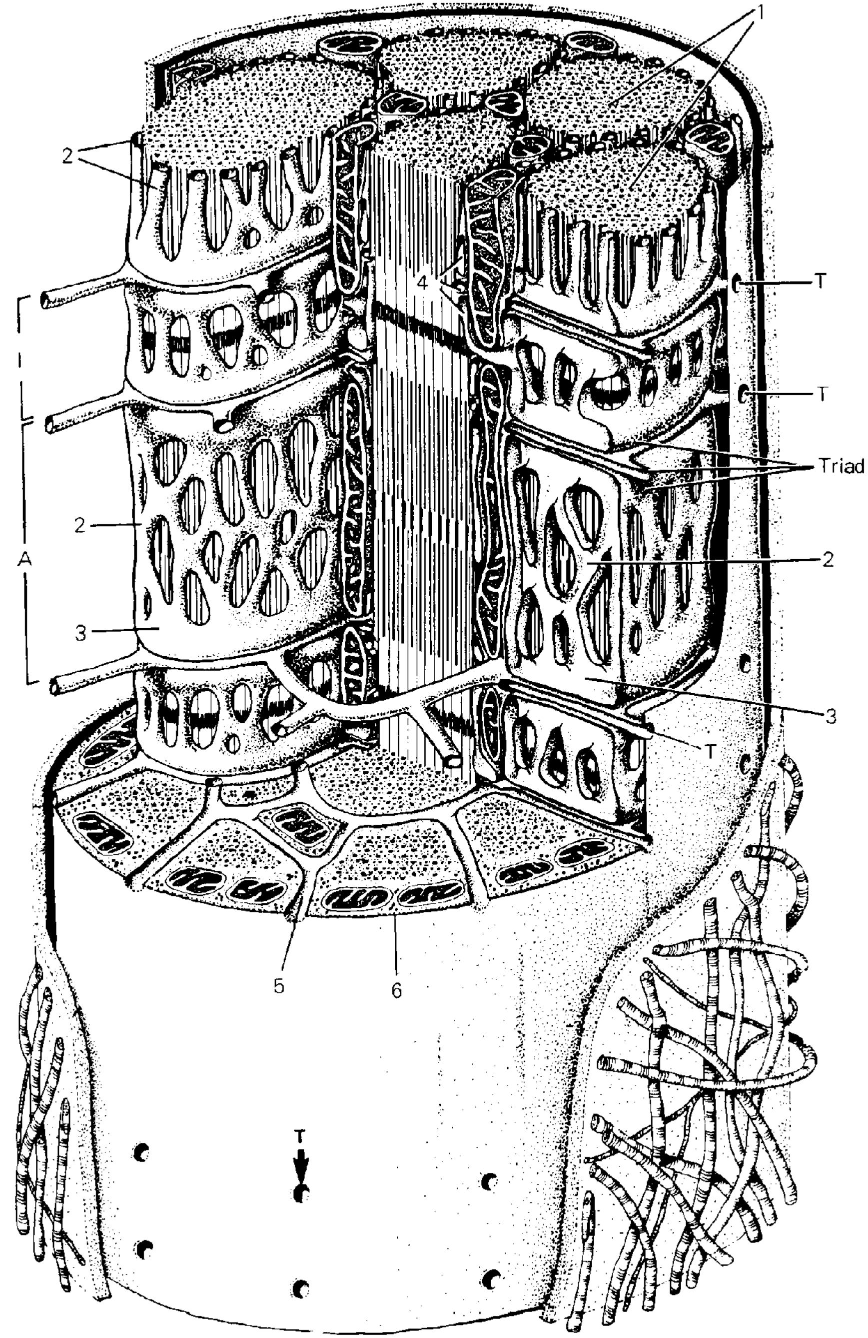
(a)



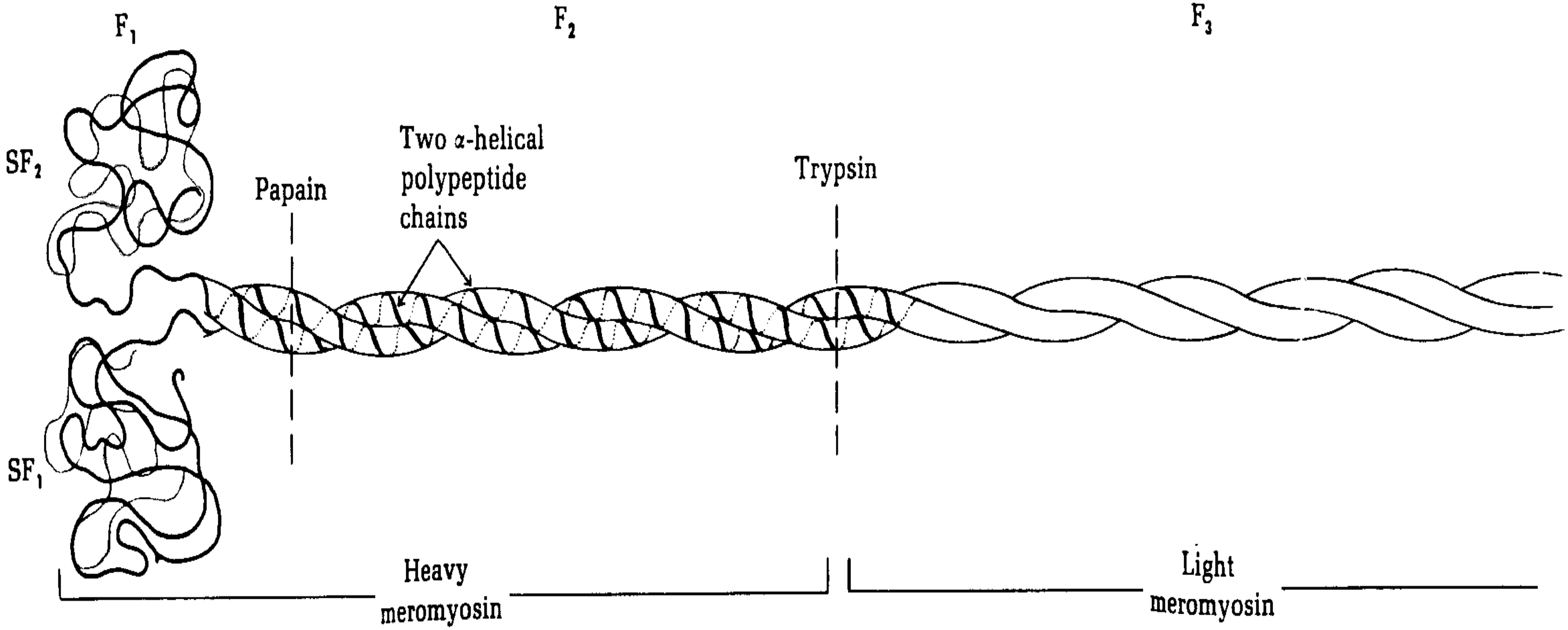
(b)

• ***FIGURE 10-21*** **Smooth Muscle Tissue.** **(a)** Many visceral organs contain several layers of smooth muscle tissue oriented in different ways. As a result, a single sectional view shows a smooth muscle cell in longitudinal (L) and transverse (T) sections. **(b)** A single relaxed smooth muscle cell is spindle-shaped and has no striations. Note the changes in cell shape as contraction occurs.


Cross-bridge
Myosin
Tropomyosin
Troponin
Binding site
Actin
Ca++
Ca++
Ca++
Ca++

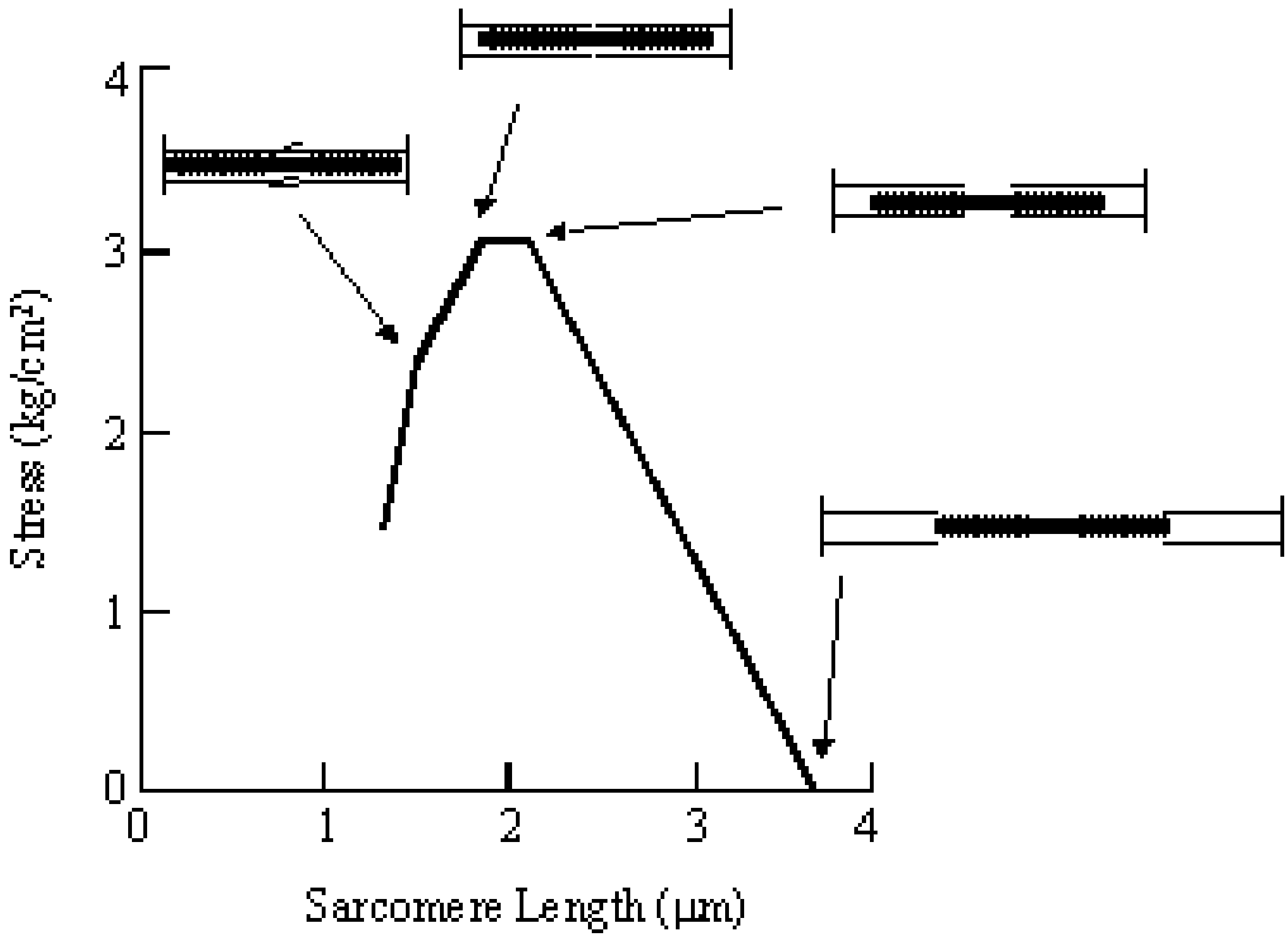


1
2
4
T
T
I
Triad
2
A
2
2
3
3
T
5
6
T

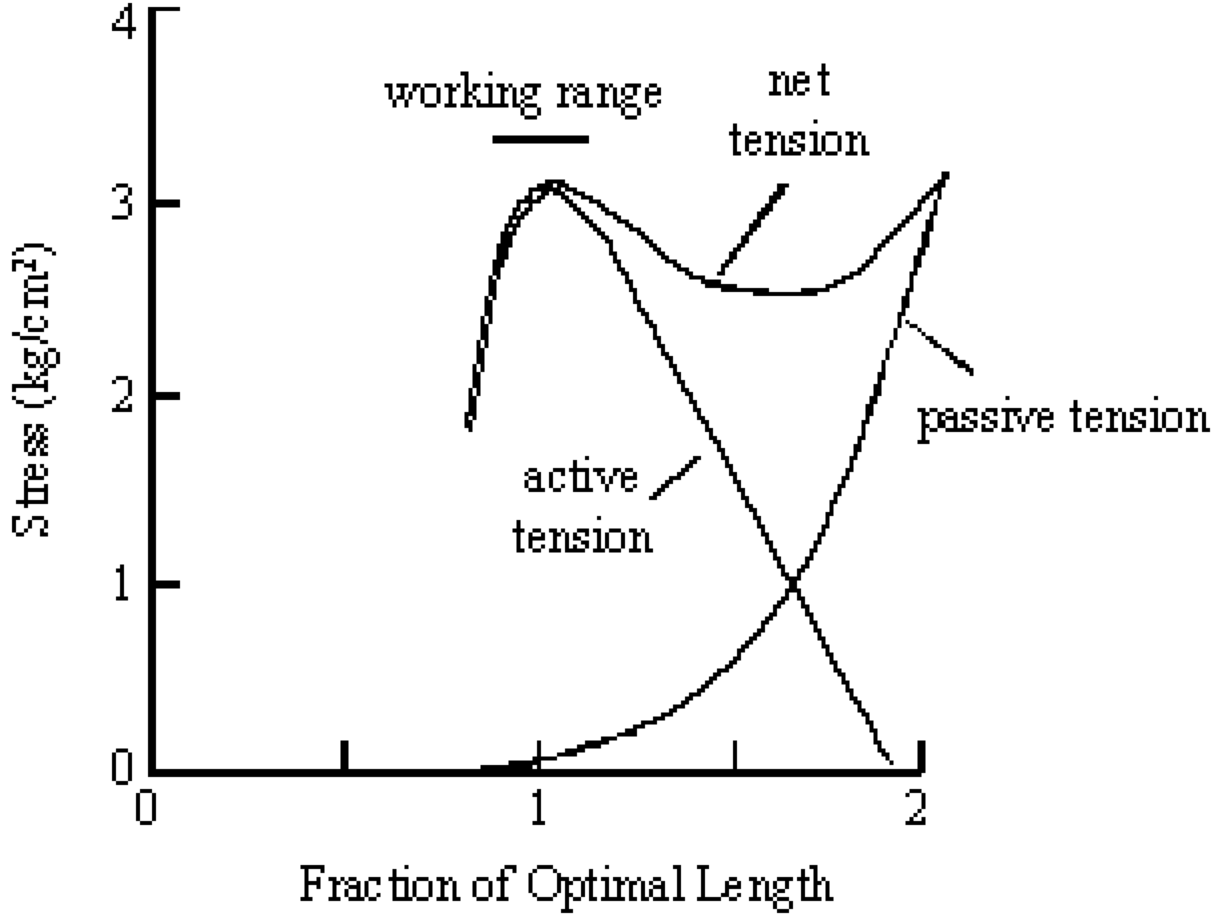


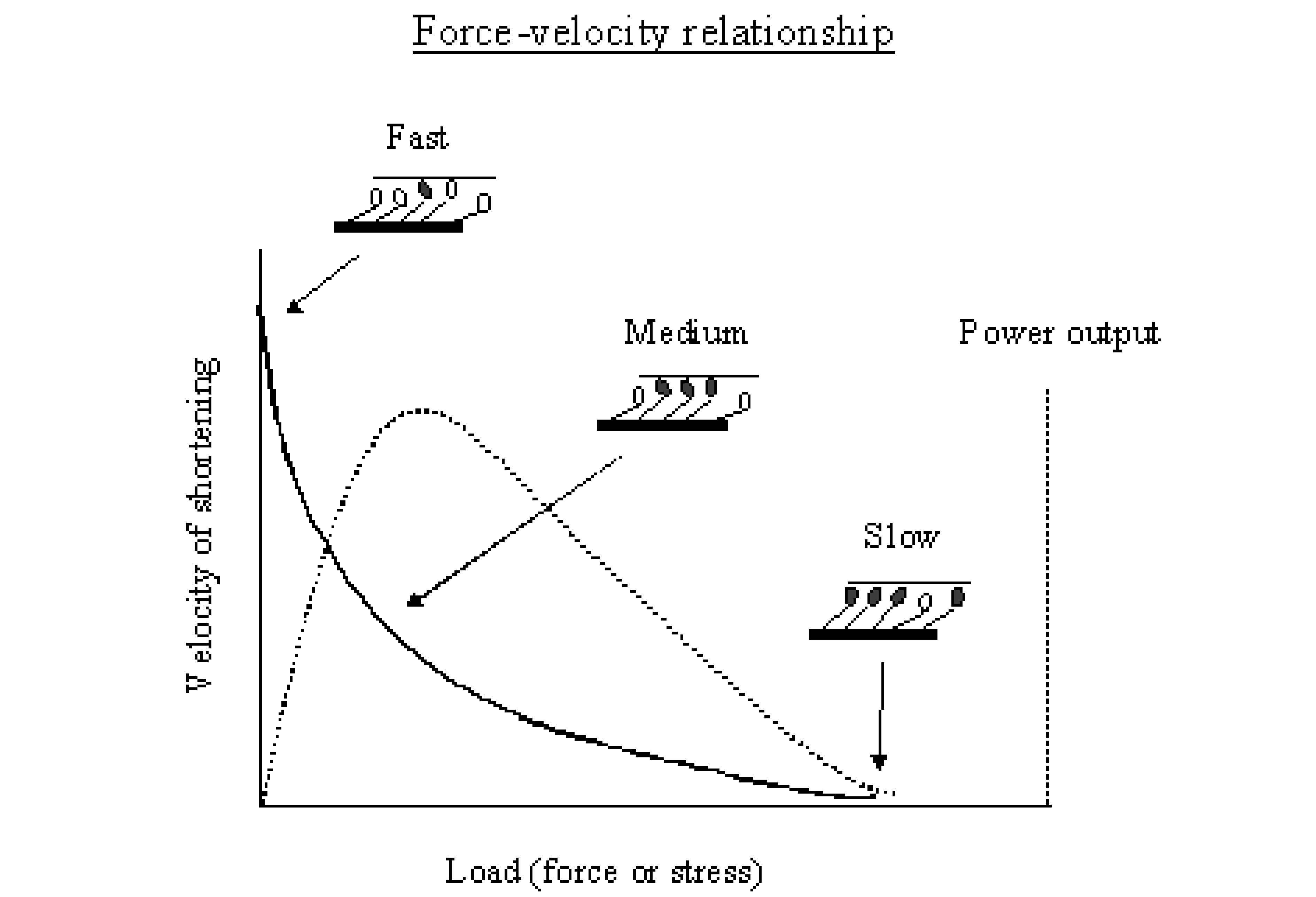
F_1
F_2
F_3
SF_2
Papain
Two α-helical polypeptide chains
Trypsin
SF_1
Heavy meromyosin
Light meromyosin

Single Fibre Length-Tension Relationship

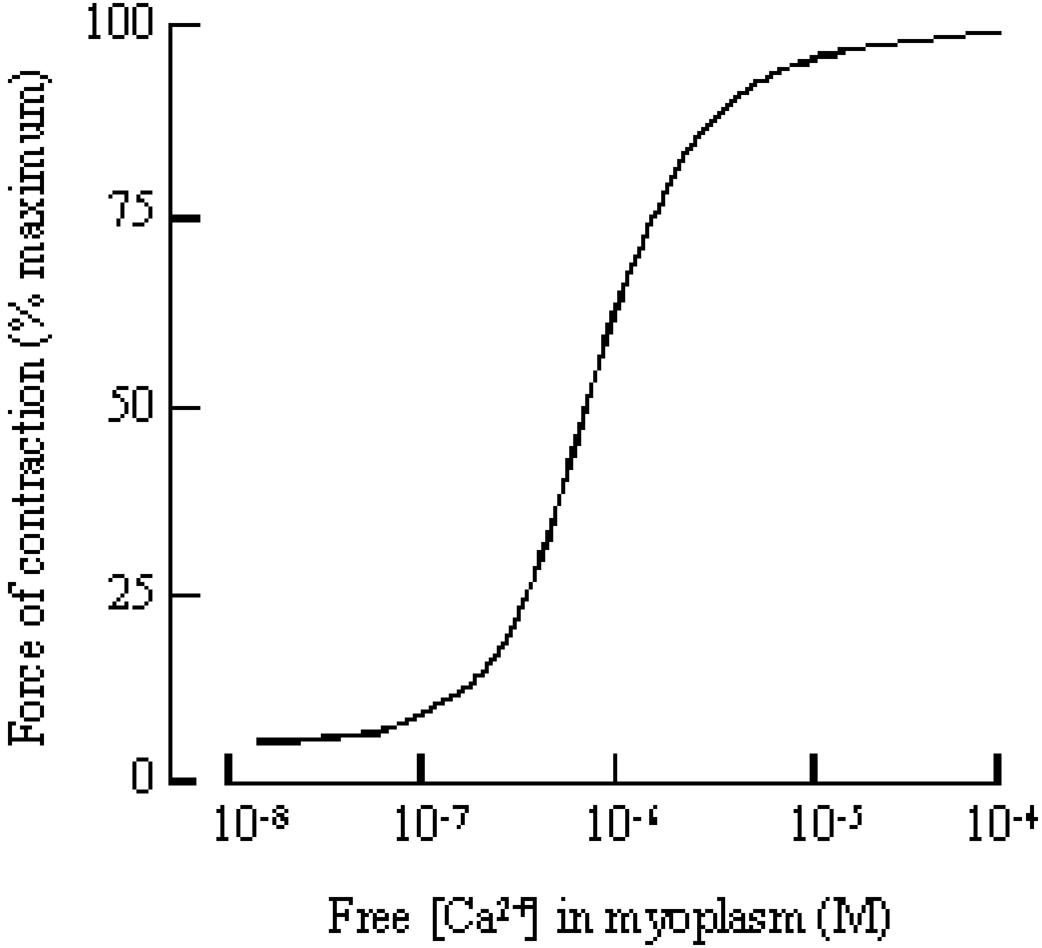


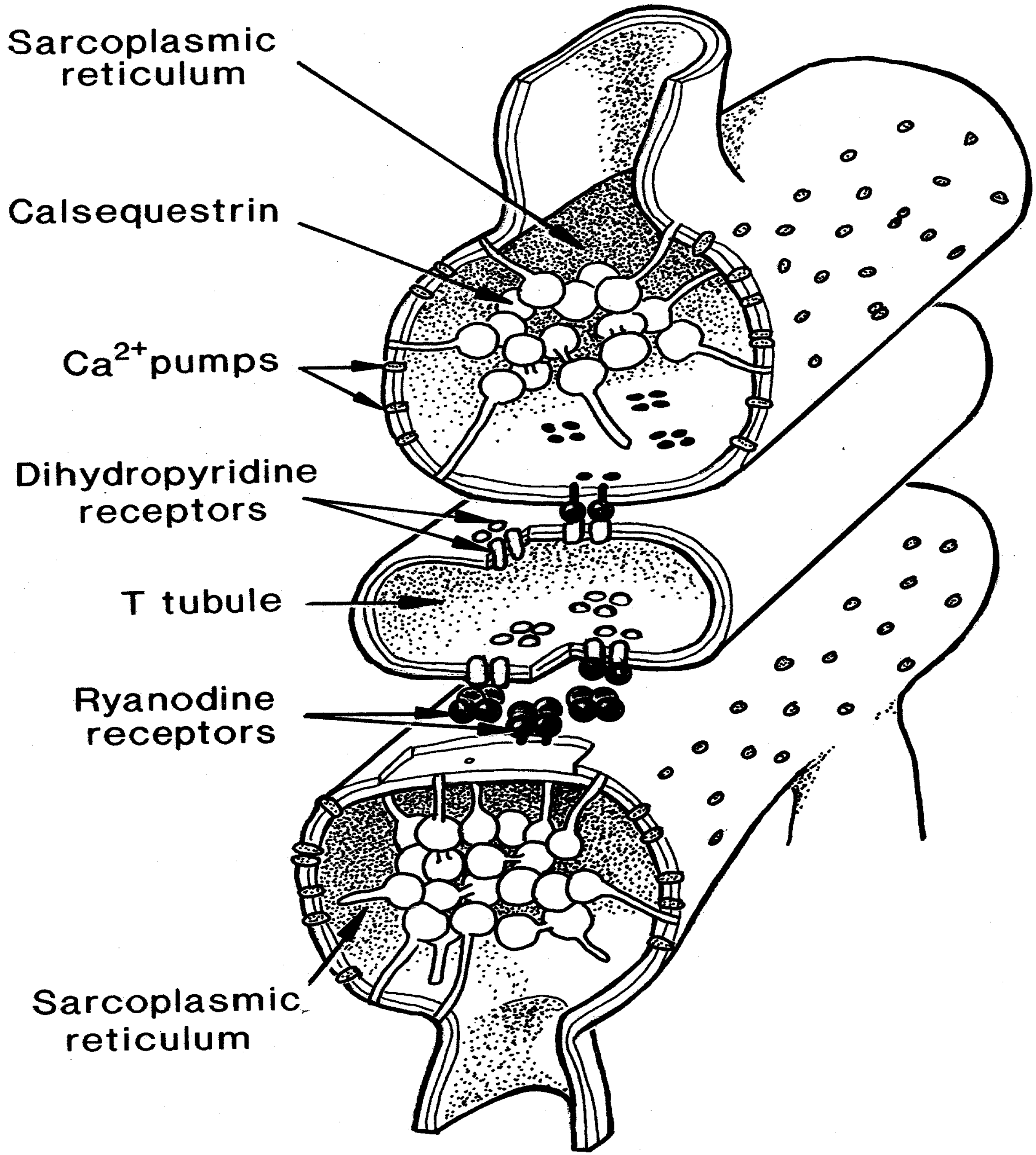
Whole muscle Length-Tension Relationship



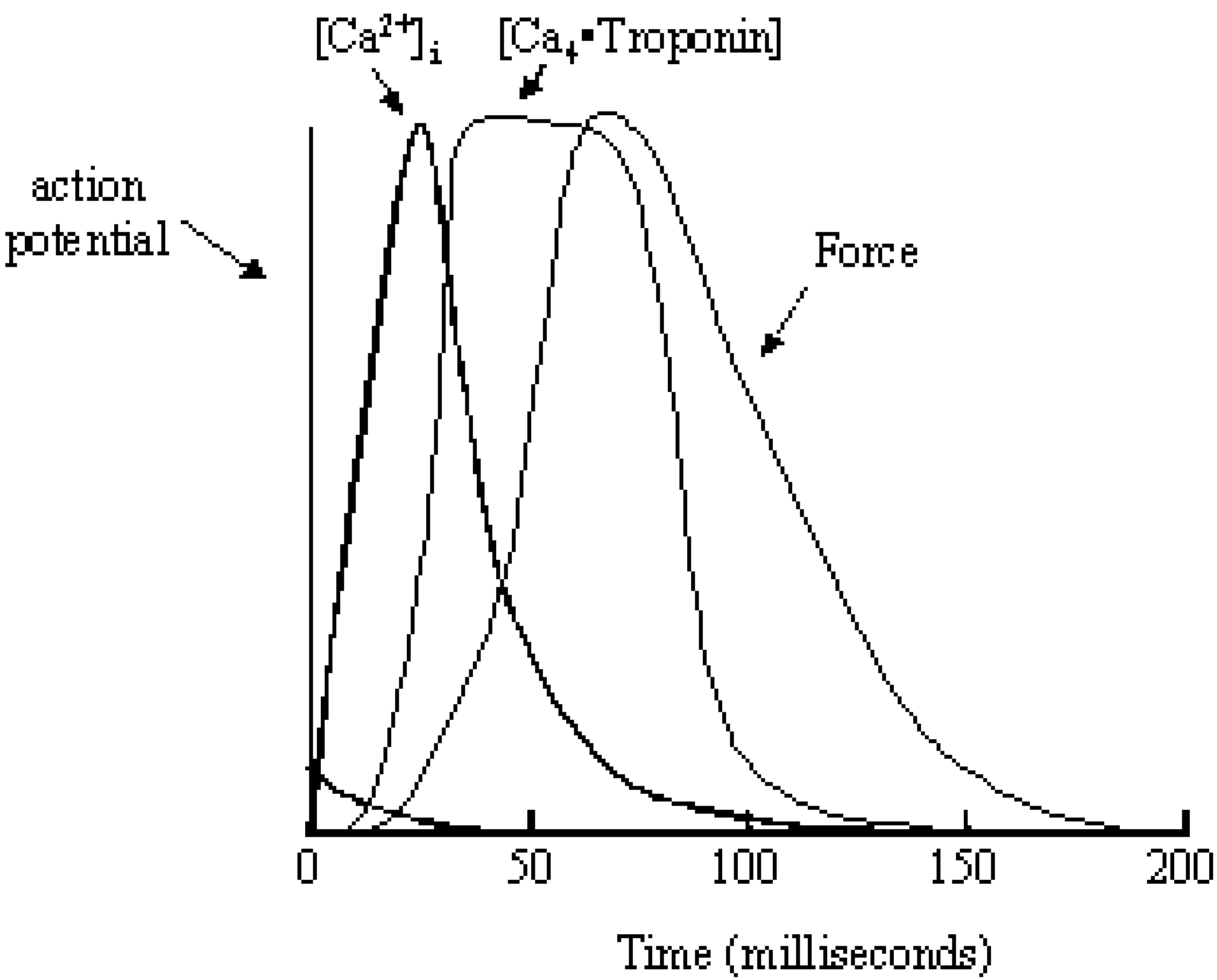

Force-velocity relationship
Fast
Medium
Power output
Slow
Velocity of shortening
Load (force or stress)

Control of crossbridge cycling by calcium

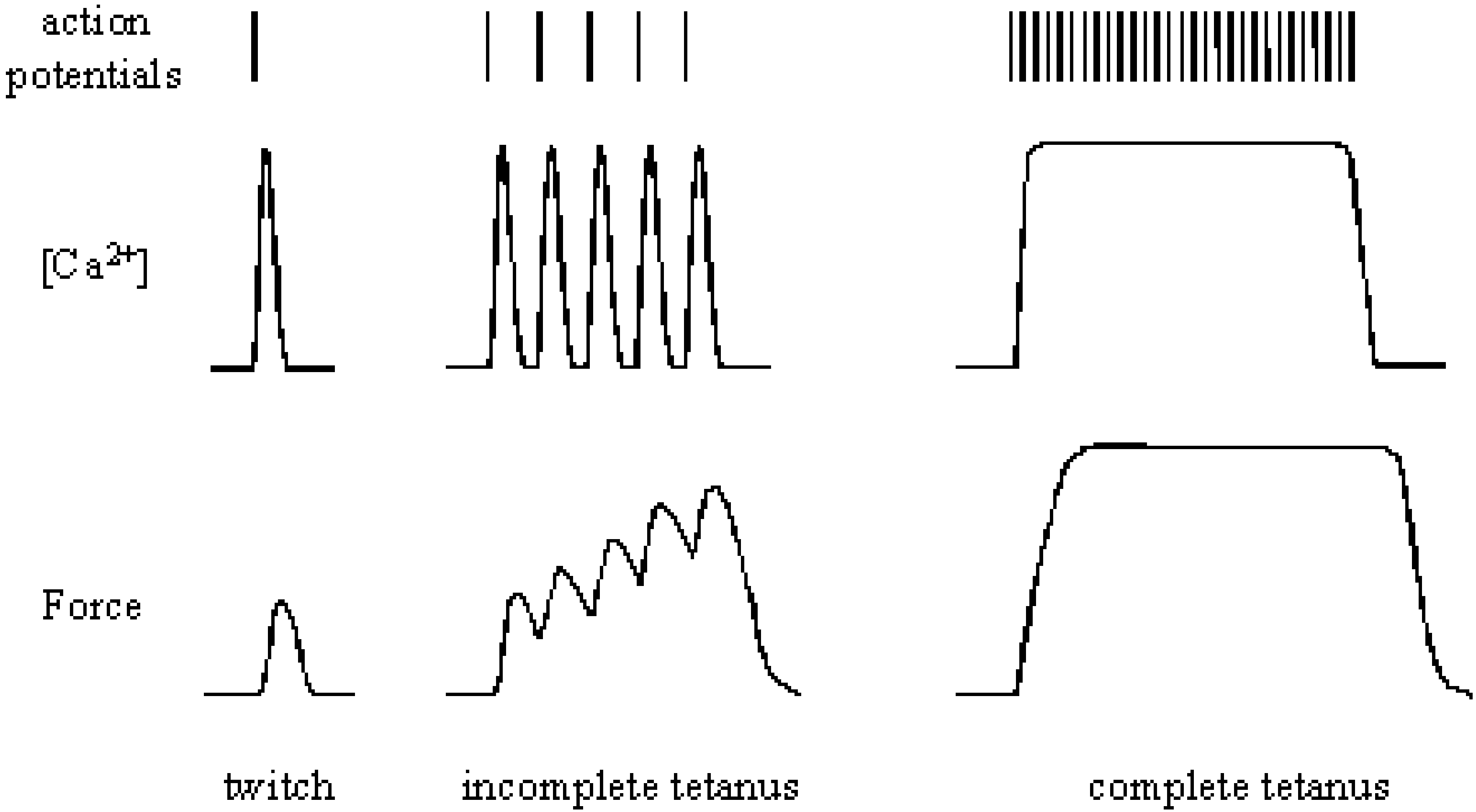



Sarcoplasmic reticulum
Calsequestrin
Ca2+ pumps
Dihydropyridine receptors
T tubule
Ryanodine receptors
Sarcoplasmic reticulum

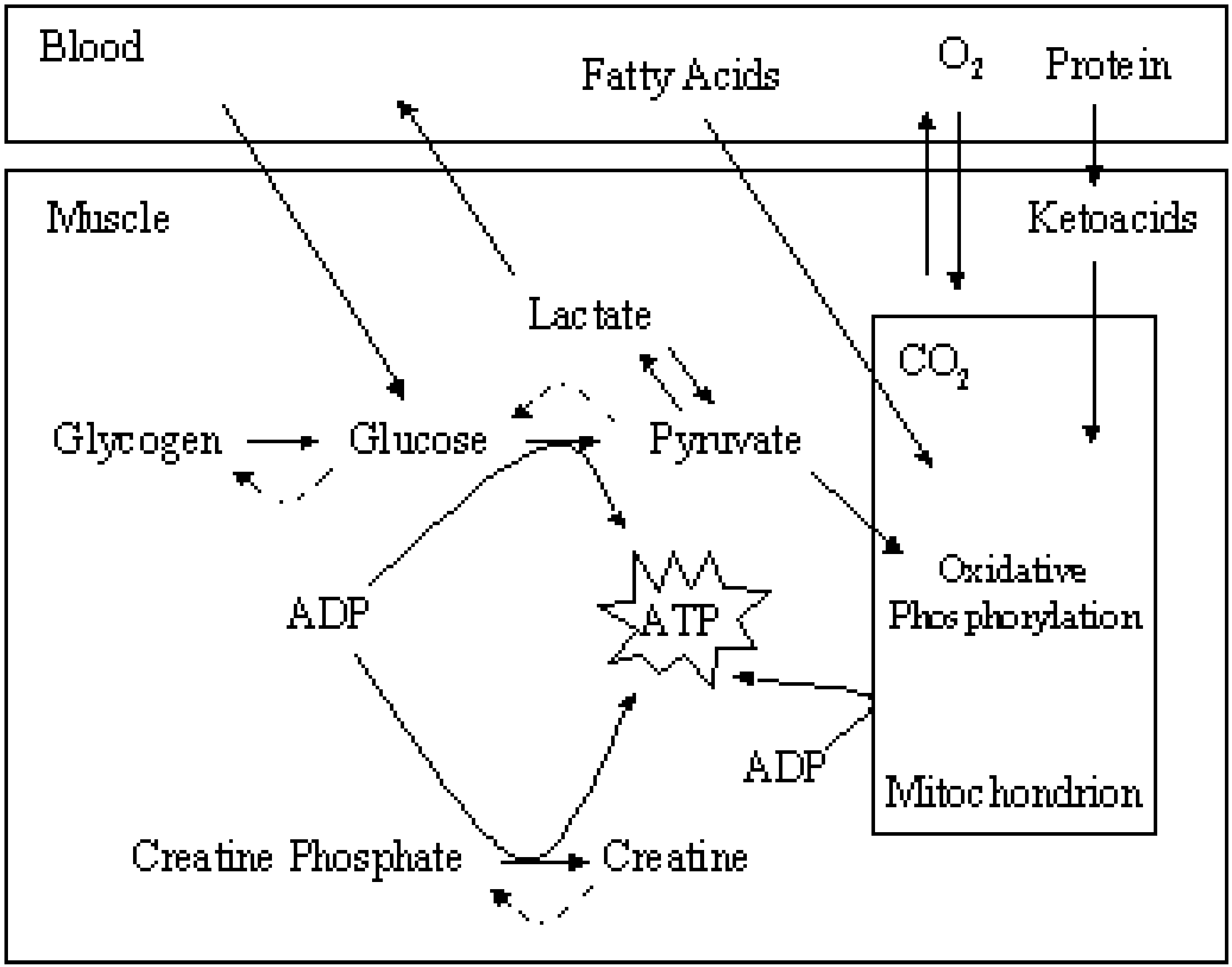
Calcium transient during a twitch



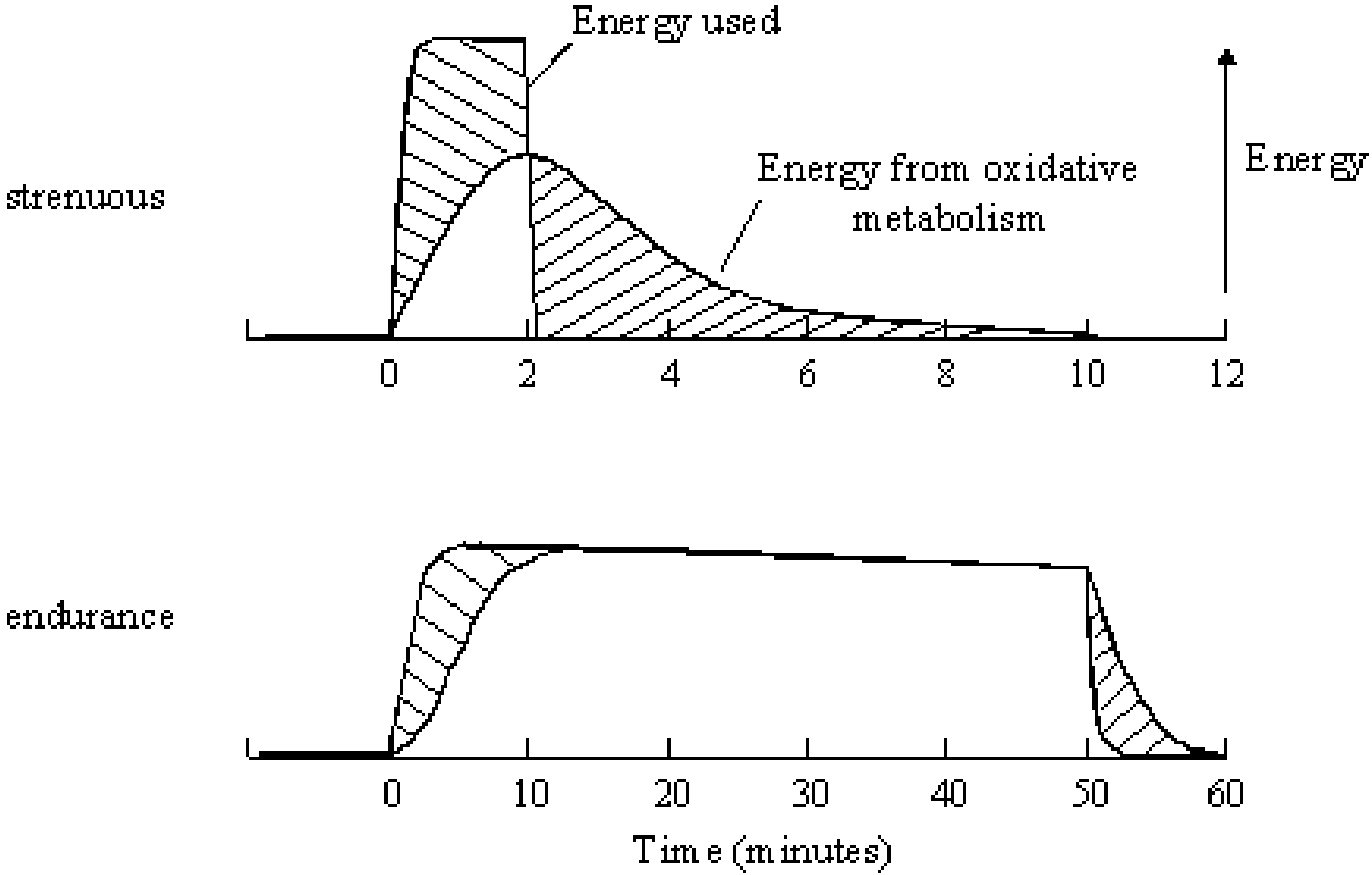
Temporal summation of $[Ca^{2+}]_i$ underlies tetanus

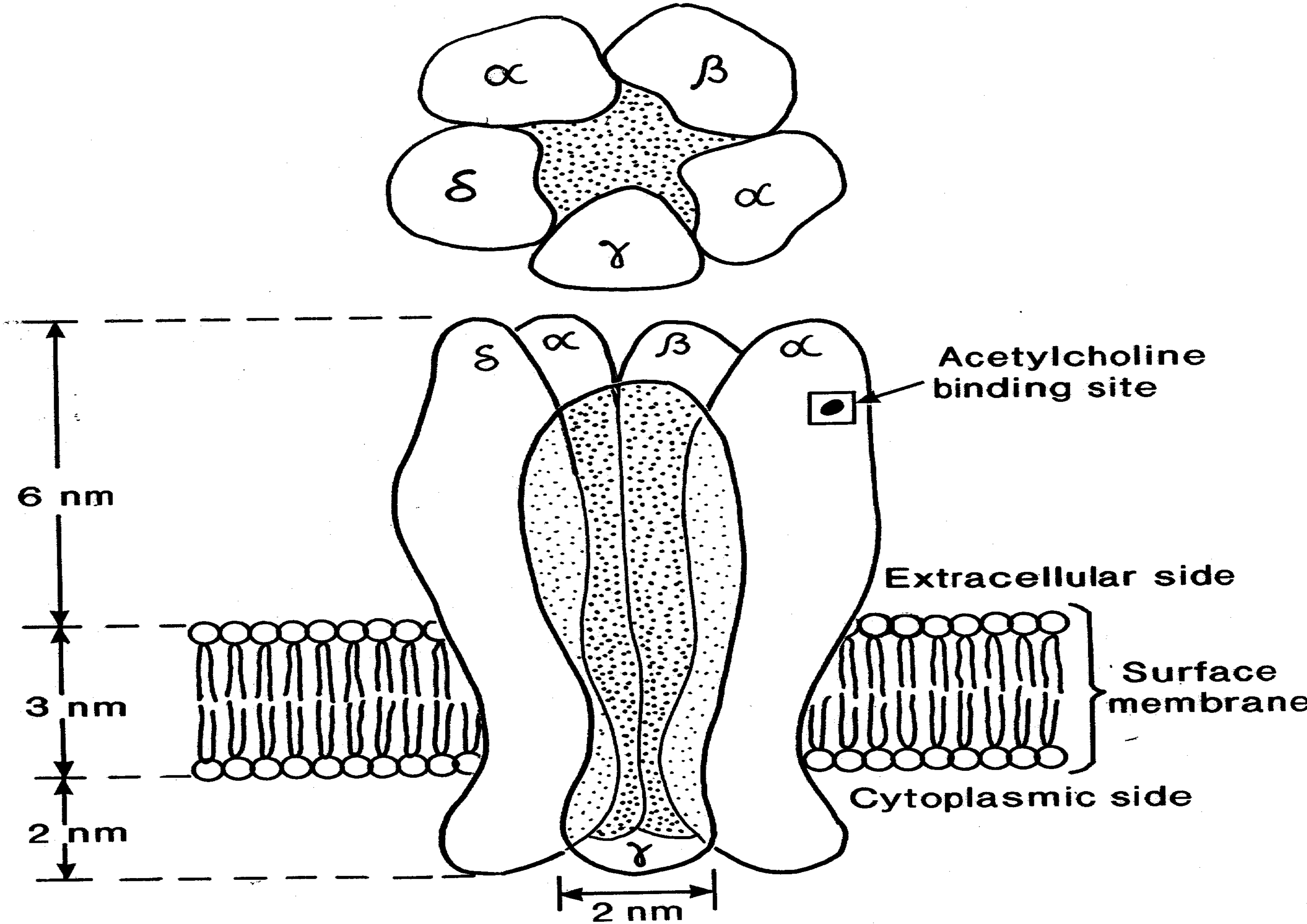


Generation of ATP in Muscle



Oxygen debt during exercise




α
β
δ
α
γ
δ
α
β
α
Acetylcholine binding site
6 nm
Extracellular side
Surface membrane
3 nm
Cytoplasmic side
2 nm
γ
2 nm

Microscopic Structure of Myofibrils

- Both of these filament types are organized into this highly structured configuration within the myofibril through a number of additional structures.
- The **Z lines** or **disks** occur in the center of the I bands and provide <u>attachment sites</u> that result in an organized arrangement of the thin filaments.

Microscopic Structure of Myofibrils

- The centers of the thick filaments are similarly aligned by cross-connecting elements of cytoskeleton which give rise to a dark **M line**.
- The repeating anatomical (and functional) unit of a myofibril that extends from Z line to Z line is called the **sarcomere**.
- The thin and the thick filaments form the contractile elements of the sarcomere and are made up of the proteins **actin** and **myosin**.

Microscopic Structure of Myofibrils

- In skeletal muscle (but not in cardiac or smooth muscle) the thin actin filaments are formed around single **nebulin** molecules.
- Thick myosin filaments form on molecules of **titin**, each of which extends from an M line to the next Z line.
- Titin probably acts as a template for formation of the thick filament, and anchors it to the Z and M lines.

Microscopic Structure of Myofibrils

- Thick and thin filaments each form a hexagonal lattice, with each thick filament equidistant from 6 thin filaments, and each thin filament equidistant from 3 thick filaments.
- Thus there are twice as many thin filaments as thick filaments.

Microscopic Structure of Myofibrils

- The thin filaments are made up of globular units of the protein **actin** together with **troponin** and **tropomyosin**, which have a regulatory function in contraction and **nebulin**.
- The actin filaments form around a single molecule of **nebulin**, which extends from a Z-line to the tip of the thin filament, and is believed to act as a template.

Microscopic Structure of Myofibrils

- **Tropomyosin** is a rod-shaped molecule about 40 nm long that forms alpha-helical subunits that become packed into the depth of the groove formed by the **intertwisted actin** chains.
- One tropomyosin molecule spans seven actin units - in resting skeletal muscle prevent the binding of these actin units to myosin.

Microscopic Structure of Myofibrils

- Reaction between the myosin head and the actin subunits is only possible if the tropomyosin molecule is moved deeper into the groove that is formed by the thin filaments.
- The latter configurational transition involving the tropomyosin is controlled by a globular protein, **troponin**, which itself consists of three, TnC, TnT and TnI, subunits.

Microscopic Structure of Myofibrils

- The tropomyosin ribbon is associated with the TnT subunit.
- The binding of 4 calcium ions triggers conformational transitions in the troponin TnC subunit that pull tropomyosin into the actin groove.

Microscopic Structure of Myofibrils

- This movement exposes the myosin binding sites present on the actin molecule, allowing binding of the myosin **crossbridges** to actin.
- The function of the third subunit of troponin, TnI, is uncertain.

QUESTIONS ?